Fixed Wireless Access 2018

Abstract: This report outlines the growing market for fixed wireless access equipment, including both licensed and unlicensed options. The scope ranges from sub-1 GHz to millimeter wave bands, including 802.11-based and 3GPP-based LTE and 5G radios.

Kyung Mun

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MOBILE EXPERTS

MEXP-FWA-18

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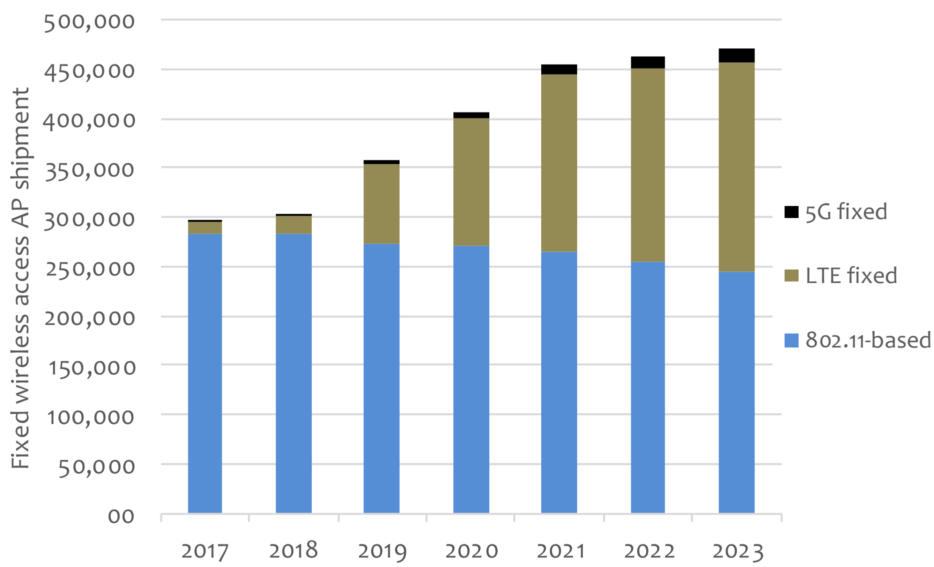
1. EXECUTIVE SUMMARY

The fixed wireless access market, excluding wireless backhaul, is expected to create nearly $20 billion of cumulative equipment revenue from base station access point (AP) and customer premise equipment (CPE) sales over the next six years. The annual sales of "dedicated" (not shared across both mobile and fixed broadband services)[1] fixed wireless AP equipment is forecasted to grow from $430 million in 2017 to $1.2 billion in 2023. Meanwhile, the CPE sales revenue is expected to remain steady at around $2.4 billion annually.

Strong underlying broadband demand, exacerbated by the cord-cutting trend, is driving the growth of fixed wireless AP shipments. This growth is further aided by government programs like CAF II auction in the USA, which incentivize operators to build broadband infrastructure in underserved areas with support of government subsidy. The economics of FWA continues to improve as new spectrum opportunities (e.g., mid 3-4 GHz and millimeter wave bands in 28-39 GHz and 60 GHz) and technology advancements, like MU-MIMO and massive beamforming, enable high throughput capacity and user speeds at low cost.



Source: Mobile Experts

Chart 1: Global DAS Market Size, including Service & Installation, 2016-2022

[1] Tier1 mobile operators are likely to share wireless infrastructure between fixed and mobile broadband services. Note that the primary base station RAN equipment sales going to Tier 1 mobile operators that are used for both mobile and fixed are not counted in our Fixed Wireless Access AP equipment sales.

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While the overall fixed wireless AP equipment market is forecasted to grow at 8% CAGR (2017-2023), the "dedicated" LTE fixed segment is expected to grow much faster, rising to nearly the same level as 802.11-based proprietary solutions in unit shipments by 2023. Telcos and larger WISPs seeking a standards-based solution with long-term technology roadmap and a large-pool supplier ecosystem will drive this growth. Meanwhile, we expect a gradual decline in unit shipments of proprietary solutions as the market consolidates and larger players gradually migrate over to LTE.

Major mobile operators--especially those holding large chunks of millimeter wave spectrum--are expected to put those assets to work with 5G fixed service launch in urban settings. This serves a dual purpose for the mobile operators as the initial 5G fixed sites eventually will get converted over to support 5G mobile use cases. With a high penetration of competitive fiber and cable footprints in developed markets, the 5G fixed market adoption will be minimal and opportunistic. With favorable near and non-line-of-sight performance and favorable economics, Mobile Experts projects a much larger adoption of LTE fixed solutions. Since the fixed wireless economics is driven by CPE cost at scale, larger operators will be drawn to the standards-based LTE systems that offer lower CPE cost.

For smaller players, the 802.11-based proprietary solutions will remain a good alternative. The lower start-up infrastructure cost of many 802.11-based proprietary systems provide cost-effective startup economics for smaller operators. For fixed wireless solutions targeting sparsely populated rural markets, 802.11-based solutions using unlicensed spectrum provides good performance-cost tradeoff. The 802.11-based proprietary solutions will remain the "workhorse" of fixed wireless access in rural markets, and the AP unit shipment of 802.11-based solutions is forecasted to remain the largest share at the end of the forecast period.

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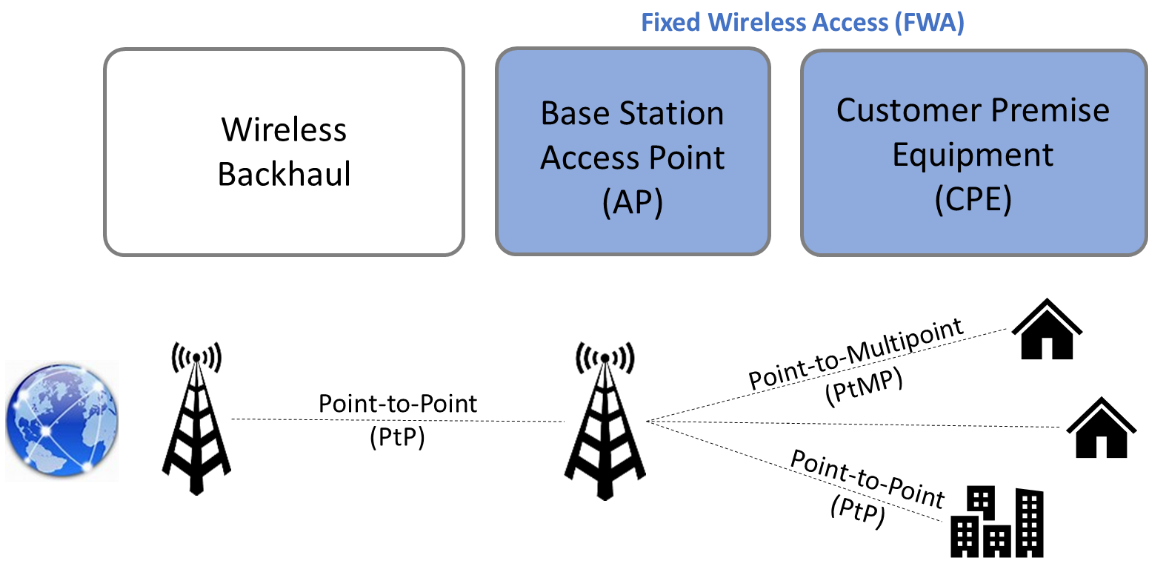
2. DEFINING FIXED WIRELESS ACCESS

In this market study, Mobile Experts is defining the Fixed Wireless Access (FWA) equipment market to denote base station access point (AP) and customer premise equipment (CPE) located on the subscriber's home or business location. The wireless backhaul equipment is excluded from our FWA equipment definition. We view the entirety of 'backhaul' plus AP plus CPE as a wider Wireless Broadband equipment market.



Source: Mobile Experts

Figure 1. Fixed Wireless Access (FWA) Market Definition

As depicted in the illustration of what's included in our FWA market definition, some portions of point-to-point radio equipment share is included in our FWA market definition if it is used for access. For example, a certain "high end" segment of the market--demanding hundreds of Mbps or even 1 Gbps service--can only be handled using point-to-point systems today. In such cases, we include this aspect of point-to-point radio equipment in our AP and CPE equipment count.

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3. MARKET ACTIVITIES

The market activities in the fixed wireless access (FWA) have picked up a notch in the past year as one of the leading mobile operators touted FWA as one of the first use cases of 5G. The increasing market activities and pronouncements around FWA and opening of new spectrum bands in the mid 3.5 GHz and the millimeter wave bands have excited long-time wireless backhaul suppliers and new operators to explore FWA once again. Also, government initiatives like CAF II funding in the USA are adding fuel to the excitement around FWA.

Demand Drivers

Market demand for broadband services is unabated around the world. As more and more people come online for common "day to day" services from communications to commerce, the need to be connected is becoming ever greater. Meanwhile, there are still many homes that are unconnected to the Internet. Even for those who have broadband services to home, the need for higher speeds seems to outpace the ability to deliver. This accelerated pace of demand is exacerbated by the cord cutting trend as well as entertainment alternatives from Netflix, Amazon, and other online streaming services become more prevalent through proliferating personal and home devices like Roku, smartphones, etc.

Connecting the Unconnected

According to International Telecommunications Union (ITU), there are over 750 million homes and businesses around the world that are still unconnected as of 2017. While this is a great improvement from 850 million unconnected homes and businesses five years ago, there is still a big chasm – 44% of worldwide households and businesses are still unconnected. Asia has the most unconnected homes and businesses (~550 million). In the Americas, including North and South America, there are still over 100 million households and businesses without an Internet connection.

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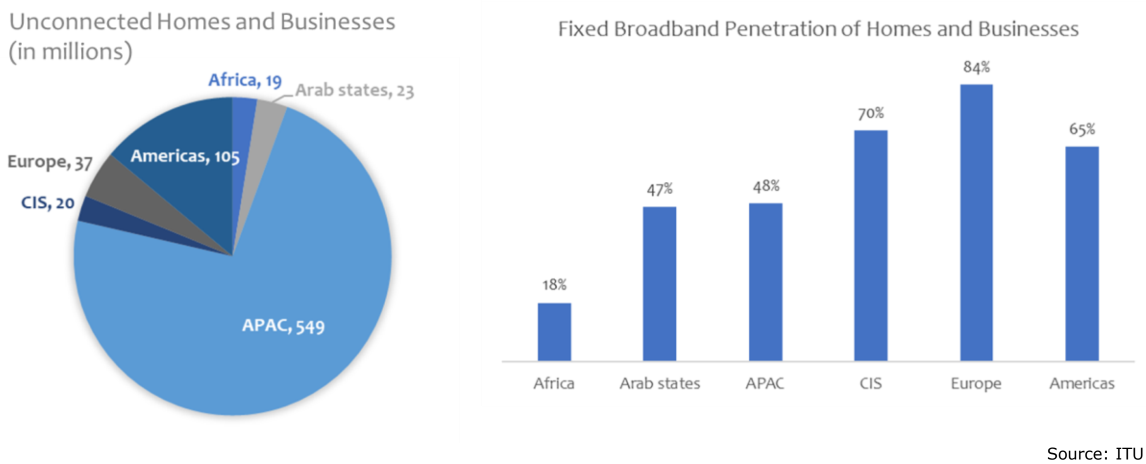

Figure 2. Fixed broadband penetration and Unconnected homes and businesses

The fixed broadband penetration varies by region as developed countries have more telecommunication infrastructure to deliver broadband services while many developing countries rely on mobile connection for broadband services. Europe has the highest fixed broadband penetration at over 80% while Africa is still under 20% penetrated.

More Speed

Even in places with high broadband penetrations, the broadband speed offer is sometimes not adequate to meet the demand. Some old telecommunication infrastructure based on copper is not capable of meeting gigabit service requirements. While fiber continues to be deployed, where it makes sense economically, it is not a panacea in all markets as the capital expenditure for wide-scale deployment is prohibitive in many markets. According to ITU, outside of APAC where fiber deployment was incentivized through government mandates and other actions, fiber comprises a relatively small portion (~15%) of overall fixed broadband subscriptions. The old copper-based DSL is still the dominant means by fixed broadband service is delivered in most places. While new technologies such as G.fast and others continue to make advancement, copper-based broadband services is likely to fade in most markets as the physical medium of copper is not conducive for handling very high throughput network services due to interference and cross-talk issues.

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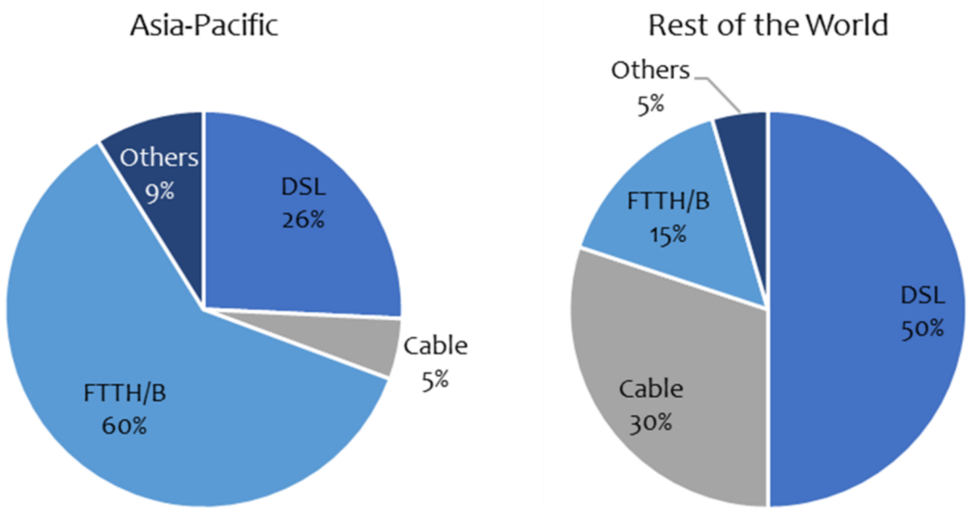
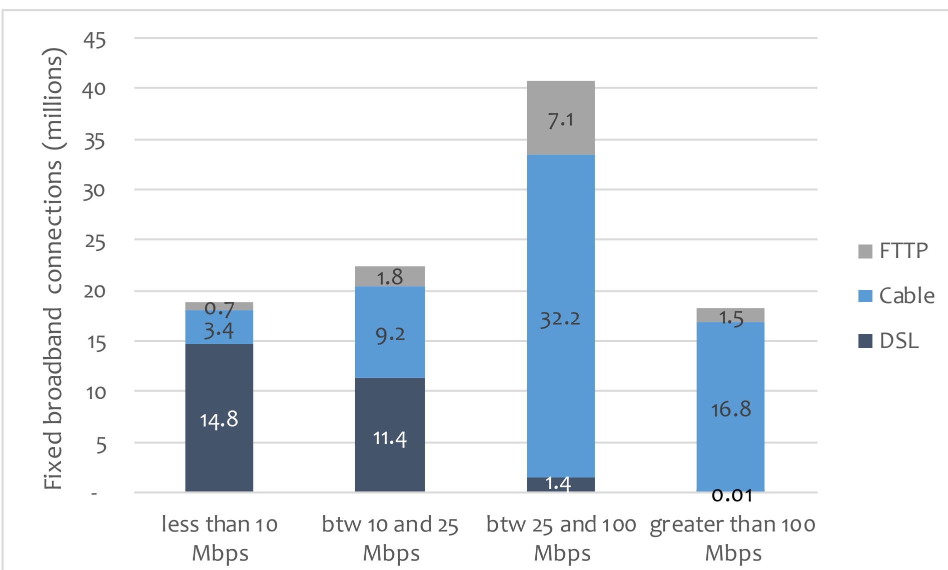


Source: ITU

Figure 3. Fixed broadband subscription share by technology

The DSL limitation as an enabling technology for high-speed Internet service can be seen in the fixed broadband connections by technology and speed for the United States. The graph below showcases the FCC broadband data as of June 2016. As clearly delineated, lower speed broadband connections (below 25 Mbps in downlink speed) are mostly served via DSL while higher speed connections are dominated by cable and fiber. According to this chart, there are about 40 million households in the USA that have fixed broadband connections below 25 Mbps downlink speeds.



Source: FCC (as of June 30, 2016)

Figure 4. USA fixed broadband connections by downstream speed and technology

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As the broadband demand increases and cable offerings look to provide "gigabit" speed offers through DOCSIS 3.1 upgrades, these underserved broadband subscribers will likely seek other high-speed broadband connections where available. In some instances where high-speed broadband connections via cable or DSL footprint is not possible (a headend is too far away from subscriber homes to deliver high-speed broadband connections), fixed wireless access may be a good fit.

Cord Cutting (Entertainment via Internet)

Another key driver of fixed wireless, and broadband service in general, is the rising Internet video consumption. According to the latest Cisco VNI study, the total Internet video traffic is expected to constitute 80% of all Internet traffic in 2021, up from 67% in 2016.[2] In particular, the cord cutting trend whereby over-the-top video streaming services like Netflix and others are delivered over the Internet is accelerating the demand for high-speed broadband services to view high-definition (HD) and 4K video on multiple devices. The disintermediation of video services independent of underlying transport network, whether that be cable or satellite TV, is especially impacting the underlying demand for high-speed broadband services in underserved areas in both rural and suburban settings.

Government Initiatives

The potential impact of Internet connectivity to positively impact people's lives is widely acknowledged by governments and world leaders. To address the large unconnected population around the globe, ITU as a part of its Connect 2020 agenda set a target of 55% of households and 60% of individuals to have access to the Internet by 2020.[3] Over 150 countries have announced their support of this global agenda and have National Broadband Plans in place, including the USA, Brazil, China, India, Australia, and other countries with large population.

Governments are leveraging multitude of different mechanisms to help foster infrastructure investments. Some are providing funding through Universal Service Funds (USF), license conditions, or opening more spectrum for mobile and fixed wireless broadband services. In the United States, for example, the Federal Communications Commission (FCC) has established Connect America Fund (CAF) to accelerate a build-out of fixed broadband infrastructure capable of delivering at a minimum, 10 Mbps downlink and 1 Mbps uplink speeds, to unconnected Americans.

[2] Cisco VNI forecast highlights: https://www.cisco.com/c/m/en_us/solutions/service-provider/vni-forecast-highlights.html
[3] ITU Connect 2020 agenda targets, https://www.itu.int/en/connect2020/Pages/default.aspx

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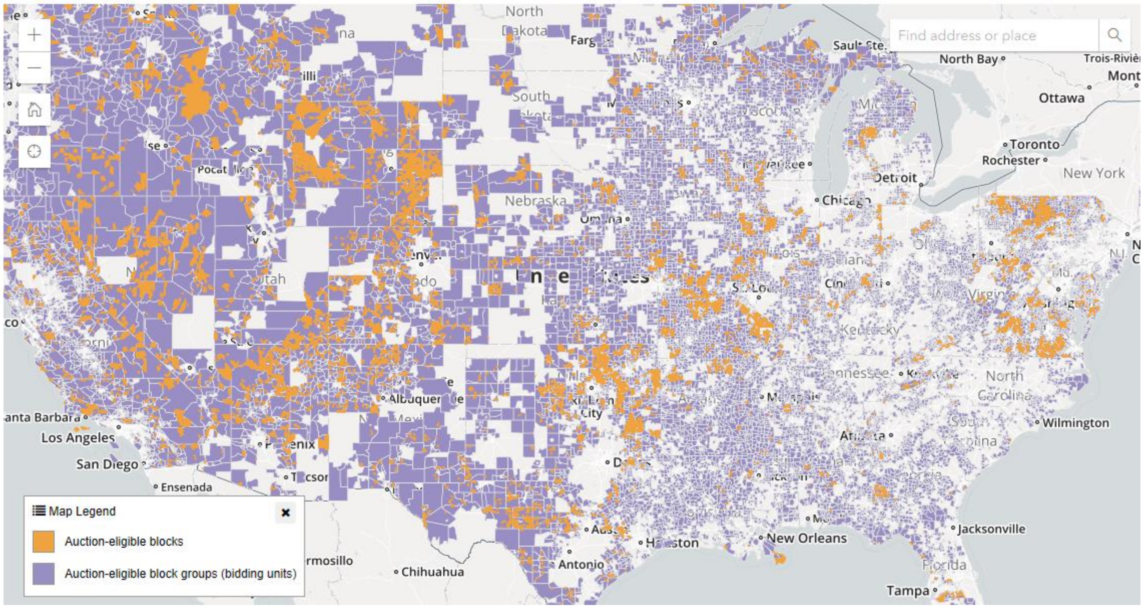

Source: FCC

Figure 5. FCC Connect America Fund II Auction Areas

FCC has set aside $1.98 B over ten years to subsidize network build-out in areas that are deemed too cost-prohibitive (i.e., too few potential subscribers to make the fixed infrastructure buildout economically unappealing). As shown above, the eligible census blocks for CAF II funding support covers a wide swath of rural America.

In addition to direct subsidy programs like CAF and other USF programs, governments are opening up more spectrum for mobile and fixed wireless applications. To help facilitate high-speed broadband experiences, regulators are opening up hundreds of MHz of licensed and unlicensed spectrum in sub-6GHz and the millimeter wave bands. There is a consensus that 3-4 GHz band will be widely used for 5G in China as well as the 28-39 GHz band in the USA and Korea for the initial 5G applications, including fixed wireless access. In addition to the unlicensed spectrum available for fixed wireless applications in the 5 GHz and 60 GHz bands, the flexible shared licensing regime like the CBRS in the USA provides innovative approach to allow access to enterprising fixed wireless providers.

Wireless Internet Service Providers

Wireless Internet service providers (WISPs) are key customers of fixed wireless access equipment. While traditional mobile carriers leverage wireless infrastructure to serve mobile consumers with their smartphones, WISPs use wireless infrastructure to deliver fixed broadband service to homes and businesses. Most WISPs are enterprising regional operators leveraging a combination of wireless and fixed infrastructure to deliver broadband data, and sometimes voice and other ancillary services, to underserved locations that larger mobile/telco and cable operators have not yet addressed. According to WISPA, an advocacy group for the WISP industry,

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there are about 3000 WISPs in the United States serving over 3 million subscribers.[4] While there is a no clear count of the total number of WISPs worldwide, Mobile Experts estimates that there are about 10,000 WISPs around the world with some larger players in parts of APAC, Europe, and South America.

Most WISPs in the United States are small to medium businesses serving local markets and regions. With start-up roots, most WISPs leverage unlicensed spectrum and 802.11-based technologies for their networks. A common network consists of a combination of licensed microwave backhaul with unlicensed access points and subscriber radio modules to connect remote homes and business locations. Rise Broadband is the largest WISP in the USA with about 200,000 subscribers. An American WISP serves, on average, 1200 customers while smaller WISPs in rural markets may only count a few hundred subscribers on their networks.[5]

Mobile / Telco Operators

Mobile operators, who are also incumbent telco operators in many markets, are leveraging their LTE mobile networks in regions where fixed broadband infrastructure is either non-existent or aging. The mobile operators are taking advantage of performance improvements in LTE to provide home broadband services to areas where ADSL can no longer satisfy the demands for high-speed broadband. Many LTE fixed home broadband services have already been launched around the globe by mobile/telco operators to strengthen their fixed broadband positions. For example, Airtel-Vodafone in India is selling its *4G Home Broadband* service to address the home broadband needs. Globe in the Philippines has been successfully leveraging its mobile network to improve its market position in fixed business, while at the same time, leveraging the common LTE network for its mobile business. It has signed up over 500,000 home broadband customers since it launched the LTE-based fixed broadband service back in 2015. Meanwhile, Bouygues in France has been selling its *4G Box* service to address the needs in underserved ADSL footprint areas.

[4] WISP Association (WISPA.org)
[5] The Carmel Group, "The BWA Industry Report 2017" white paper for WISPA

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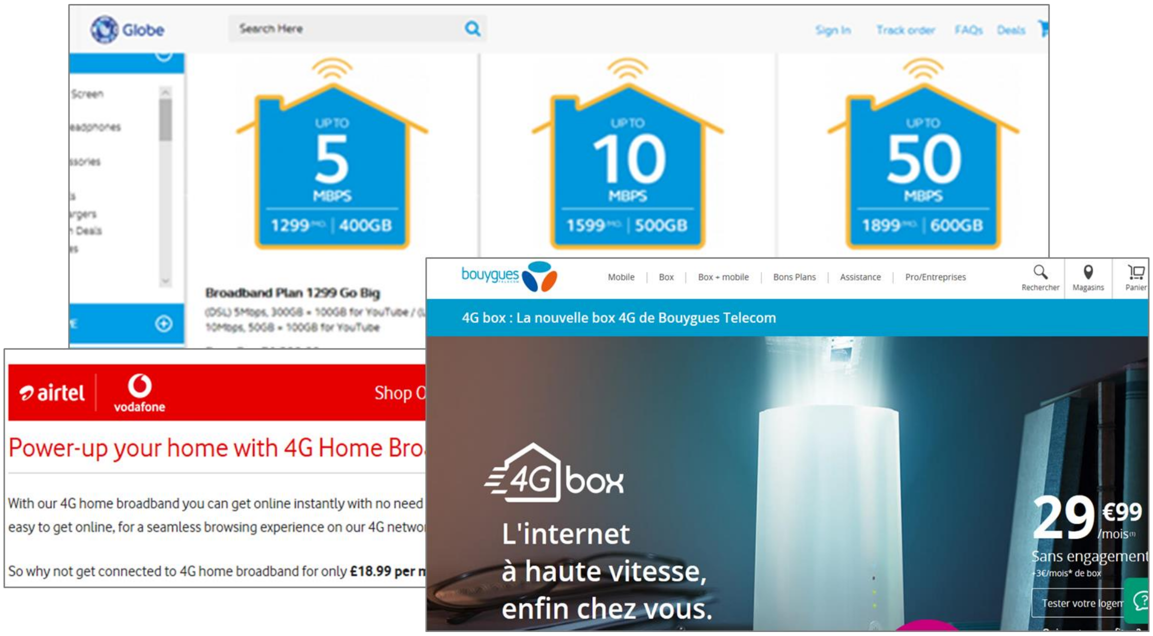

Source: company websites

Figure 6. LTE fixed home broadband services launched by Mobile/Telco operators

As the operators continue to adopt LTE Advanced features such as Carrier Aggregation, LAA, etc., the speed performance of LTE fixed wireless services is likely to go up.

In the USA, mobile operators have not yet widely adopted LTE fixed wireless services. Their focus is, first and foremost, serving the growing mobile data traffic. Adding additional traffic, especially those of home broadband service that consume a lot more GB data than mobile, may damage the overall network performance. Taking a risk of servicing both mobile and home broadband services via a common LTE network may be too big for the mobile operators to take, considering that they derive 10-40x premium of servicing mobile traffic over fixed.[6] Moreover, the mobile operators have a smaller share of fixed broadband market in the USA as cable penetration is high compared to other regions.

While the appetite for using LTE network to serve home broadband service is low in the USA, the CAF II funding is generating a lot of interest in fixed wireless access. The favorable economics and possible new spectrum opportunity in the mid 3 -4 GHz band have generated a renewed interest in fixed wireless technologies. Some operators are readily deploying fixed wireless access to meet its CAF commitment. For example, AT&T is using its WCS spectrum as a dedicated carrier to provide "10

[6] Author's blog on "mobility premium" trend: https://www.fiercewireless.com/wireless/industry-voices-mun-mobile-pricing-drops-from-9-gb-to-1-80-gb-just-1-year

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Mbps down/1 Mbps up" fixed broadband service to homes and businesses in rural communities as a part of its CAF commitment. AT&T's Fixed Wireless Internet service is expected to reach 400,000 locations in 8 states by the end of 2017 and over 1 million locations by 2020. While AT&T can deploy fixed wireless service readily using its licensed spectrum, many telcos without licensed spectrum will be keen to leverage unlicensed or less expensive shared spectrum fixed wireless technology. With the government support of several hundred million dollars each, AT&T, CenturyLink, Frontier, and Windstream are expected to seriously consider fixed wireless access as a part of their technology toolset in delivering the mandated 10/1 and 25/3 Mbps broadband speeds to "eligible locations" in rural America.

Nationwide Summary

PC Carrier	Eligible Locations	Support Amount
AT&T	1,265,036	$493,973,528
CenturyLink	1,190,016	$514,334,051
Cincinnati Bell	7,084	$2,229,129
Consolidated Communications	24,698	$13,922,480
Fairpoint Communications	106,380	$38,193,432
Frontier Communications	659,587	$283,401,884
Hawaiian Telcom Inc	11,081	$4,424,320
Micronesian Telecom	11,143	$2,627,177
Verizon	387,470	$143,924,995
Windstream Communications	413,345	$178,779,073
Total	**4,075,840**	**$1,675,810,069**

Source: FCC

Figure 7. CAF II eligible locations and support funding to respondent carriers

Over-the-Top Competitive Carriers

Besides the WISPs and mobile/telco operators, another class of operators are taking great interest in fixed wireless access. These so-called "over the top" (OTT) competitive carriers view broadband connectivity as an adjacent market opportunity that also enhances their primary businesses. With favorable market developments in technology, spectrum, and economics, OTT carriers see fixed wireless access as a possible means to create the broadband connectivity business. Some example companies in this category include Google, Vivint, Amazon, Dish, and cable operators. Even though Google's broadband ambition has cooled considerably since the early days of Google Fiber, and more recently its Webpass acquisition in 2016, we believe

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fixed wireless access will remain a credible technology option for OTT carriers to opportunistically get into the fixed broadband business.

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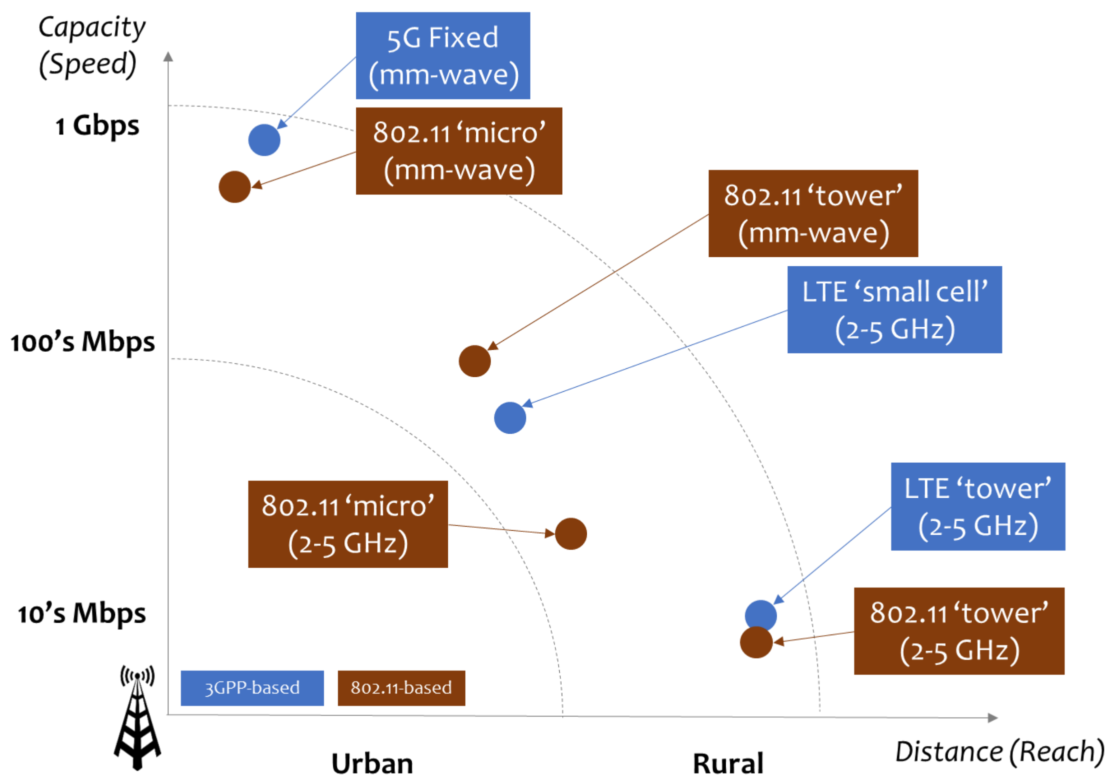
4. Technology and Spectrum Landscape

All fixed wireless access technologies aim to maximize distance reach and throughput capacity at low cost. To achieve this lowest possible "cost per bit" economics, various fixed wireless technologies and proprietary vendor solutions incorporate different spectrum and interference mitigation strategies to offer low "cost per GB" access system to service providers.

In this report, we broadly categorize fixed wireless access (FWA) technologies into the following:

- 802.11-based/proprietary
- 3GPP-based (LTE and 5G)

Both 802.11-based and 3GPP-based fixed wireless technologies can enable different "speed vs. reach" combinations for rural, suburban, or urban settings based on spectrum and deployment architecture selections as illustrated below.



Source: Mobile Experts

Figure 8. Technology, spectrum, and architecture to optimize speed and reach

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Spectrum selection is a primary determinant of the "speed vs. reach" tradeoff in a fixed wireless system. To reach higher user speeds, more spectrum is needed. And, large chunks of channel bandwidth are mostly found in the higher millimeter wave bands. However, the higher frequency bands have shorter reach due to high attenuation. Thus, the use of millimeter wave bands will likely be confined to denser suburban or urban environments. Meanwhile lower frequency bands will be preferred in sparsely populated rural markets where the design goal is to maximize reach and coverage.

It should be noted, however, the millimeter wave band with more capable CPE and outdoor antenna placement can extend the range and coverage of a FWA system, even in the millimeter wave case.[7] This is yet another tradeoff that a service provider or a system designer can make – i.e., leverage a costly CPE to extend range and throughput, or a cheaper CPE and operate at a shorter range and coverage.

Deployment architecture and antenna placement can also impact the speed vs. reach tradeoff. A traditional deployment architecture where a base station is mounted on a tower above the clutter provides a maximal reach and coverage. In contrast, placing a base station below the clutter, on top of a "hub home" or utility pole, for example, can limit the range of fixed wireless AP. If the design goal is to densify the network to effectively increase user speeds by limiting the sector capacity available to fewer users, then the "micro hub" deployment may be suitable. Otherwise, traditional tower architecture provides the best coverage, especially at lower bands.

802.11-based (Proprietary) FWA Technologies

The 802.11-based unlicensed radio products were instrumental in creation of the fixed wireless market. Inexpensive unlicensed radios enabled enterprising companies to cost-effectively build wireless transport networks to connect unconnected or underserved rural markets where laying broadband wireline infrastructure is uneconomical. Companies like Ubiquiti, Cambium, and others were instrumental in producing low-cost point-to-point (PtP) backhaul and point-to-multipoint (PtMP) access point and subscriber unit products to jump-start the market.

In the early days, companies took low-cost Wi-Fi chipset solutions and customized Layer 2 (MAC) and above to create proprietary solutions specifically designed for fixed wireless access and transport. In general, 802.11-based proprietary fixed wireless solutions have added the following features to overcome some of the key drawbacks of Wi-Fi standard:

[7] Mobile Experts believes that Starry has purposely designed its system to operate at maximal range and coverage at the millimeter wave band (~1 km at 37 GHz) which requires a complex and costly CPE (vs. a system that operates at a shorter range and coverage but requiring less expensive CPE).

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- *Coordinated Scheduling (TDMA/TDD)* – A key drawback of Wi-Fi chipsets is that Wi-Fi standard uses contention-based CSMA/CD in which all devices compete for over-the-air resources until they succeed. In this "uncoordinated" fashion, a lot of airtime is wasted when packet collisions occur between AP and CPEs. Some vendor solutions correct this by creating TDMA/TDD framework so that the packet delivery between AP and subscriber CPEs can be coordinated.

- *"GPS Sync"* – Many 802.11-based fixed wireless solutions have now adopted this feature to have all AP's to transmit at the same time, and then receive data from CPE's at the same time as well. This way, possible interference between AP's on the same channel can be mitigated. Also, the GPS Sync essentially allows frequency reuse in a scenario where four AP's are deployed at a site, in 90-degree sector configuration. Instead of using four separate channels at the site to avoid self-interference, one can use two channels (channels A and B) where one set of "back to back" AP's (in the 4-sector site) use the channel A while the other set of "back to back" AP's use the channel B.

- *Multi-User MIMO (MU-MIMO)* – The MU-MIMO operation essentially allows an AP to steer simultaneous beams to different users with each beam containing specific packets for the intended client user. It effectively increases capacity and offer higher speed per user. While the 802.11ax standard defines a maximum number of MU-MIMO transmissions to eight, some vendor solutions have taken this to a higher order. For example, Cambium's cnMedusa product supports 14x14 MU-MIMO.

Instead of the "brute force" method of applying wider channels (more spectrum) or higher modulation (e.g., 256 QAM) to overcome the inefficiencies of 802.11 standard, these "coordination" features allow more efficient usage and allocation of airtime.

To make necessary customizations, 802.11-based proprietary fixed wireless product companies have strategic relationships with Wi-Fi chipset companies. For example, Mimosa Networks uses Quantenna's Wi-Fi chipset in its product while Starry's millimeter wave product is believed to be based on Marvell's Wi-Fi chipset solution. Some have chosen to create own chipset solution using FPGAs to truly create a custom fixed wireless solution. A good example is Cambium whose PMP 450 platform is considered one of the more robust fixed wireless solutions in the market. To compete against low-cost vendors like Ubiquiti and Mikrotik, Cambium also offers a Wi-Fi chipset-based product, ePMP, which has less features than its flagship PMP 450 product.

Although most 802.11-based proprietary solutions start off with a low-cost Wi-Fi chipset solution that may be 6x cheaper than LTE at the chipset level, many

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proprietary vendors take on the additional R&D cost of making customizations on top of standard "merchant" silicon. In some respects, the 802.11-based proprietary vendors have limited scale to drive down the cost of their equipment at scale, especially CPE's. It's a bit ironic that proprietary 802.11-based solutions are protected from commoditization because they're customized, but it's also difficult to achieve cost reductions. In this way the 802.11 based vendors have a difficult time selling to to large-scale operators, where overall ROI is primarily driven by the CPE cost (see the section on "*Unit Economics of Cost to Pass and Cost to Connect*" below).

3GPP-based FWA Technologies

The 3GPP ecosystem continues to make great strides as it marches towards 5G commercialization. As the 3GGP technology evolves towards 5G, LTE continues to deliver. With Carrier Aggregation, 4x4 MIMO, and 256 QAM modulation combinations, LTE can deliver a peak throughput capacity of 1 Gbps using only 60 MHz of spectrum. This implies that using an over-subscription factor of 10:1, an LTE small cell supporting 100 subscribers can theoretically provide ~100 Mbps per user at a "Gigabit LTE" site. With large spectrum bandwidth available in the millimeter wave bands, 5G fixed wireless promises 1 Gbps user speeds (under ideal settings).

LTE Fixed

LTE with massive MIMO (64T64R) can deliver a significant capacity boost. As shown below, Huawei has successfully managed to deliver close to 100 Mbps LTE fixed wireless broadband service using 40 MHz of spectrum, massive MIMO, and 2T4R LTE CPE's. With additional spectrum bandwidth coming available in the sub-6 GHz[8] and 28/39 GHz band, Huawei believes that fixed wireless offers incremental market opportunity for its core service provider customers. The company is positioning massive MIMO on base station AP's and high-order MIMO on CPE's to extend the range and capacity of fixed wireless systems.

[8] likely the 3-4 GHz band positioned for 5G in China, Europe and other regions

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Source: Huawei

Figure 9. LTE and 5G performance improvements provide lower "cost per bit" transport

With LAA and higher order MIMO support, the business case for LTE Fixed continues to get stronger as the LTE feature set improves.

5G Fixed

With larger chunks of spectrum in the 3 – 4 GHz and 28 – 39 GHz bands and lower latency capability, 5G offers tremendous option for fixed wireless application. The use of massive beamforming at high millimeter wave frequencies makes it easier to provide coverage, especially in the fixed wireless context, since narrow beams can be directed to fixed locations (unlike in the mobile case). Moreover, the MU-MIMO operation allows the signals from multiple CPE's to be multiplexed simultaneously on the same channel in different beams, thus providing greater spectral efficiency and high peak throughput capacity which yields higher user speeds.

Based on Verizon's 5G fixed wireless pre-commercial trials in 11 markets, the 5G fixed millimeter wave system has shown very good results showing ~1 Gbps median download speeds for cases where a 5G fixed base station AP range was less than 2000 feet.

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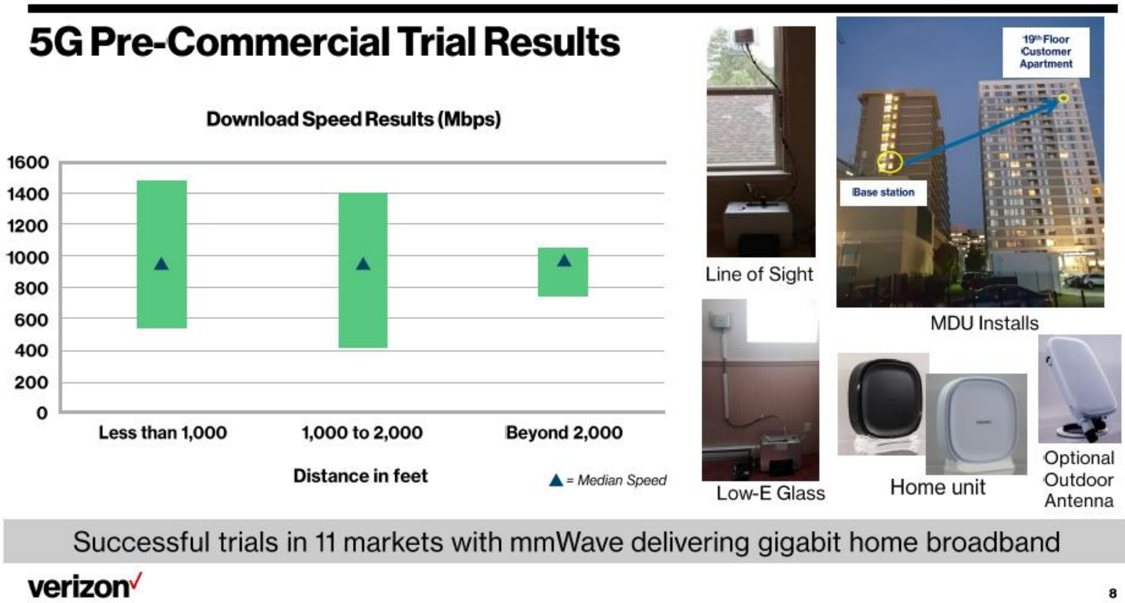

Source: Verizon,"Sellside Analyst Meeting," Nov.29,2017

Figure 10. Cost to pass and connect a subscriber via FWA vs. FTTH

Operating above 20 GHz, the placement of subscriber CPE antenna will be critical in achievable range, and consequently cell edge performance. According to Ericsson, a base station above clutter (on tower above tallest trees) provides the best range while placing CPE antenna above the roof at subscriber homes provides the best result since such deployment yields higher line-of-sight probability between the CPE antenna and the base station AP. The relative cell range between 3.5 GHz and 28 GHz bands is about 10x difference as shown below.

Cell range	Base Station AP above clutter		Base station AP below clutter	
	3.5 GHz	**28 GHz**	**3.5 GHz**	**28 GHz**
Indoor CPE antenna	2.5 km	250 m	1.8 km	180 m
Outdoor CPE antenna	5 km	500 m	2.5 km	250 m
Rooftop CPE antenna	100 km	10 km	3.5 km	350 m

Source: Ericsson Technology Review, "5G and Fixed Wireless Access," Dec 2016

Figure 11. Impact of AP and CPE antenna placement on FWA cell range

802.11-based vs. 3GPP-based FWA

Making a direct comparison between the two broad classes of fixed wireless access technologies (802.11-based proprietary vs. 3GPP-based) can be problematic as 802.11-based proprietary solutions have very wide variances in performance and cost.

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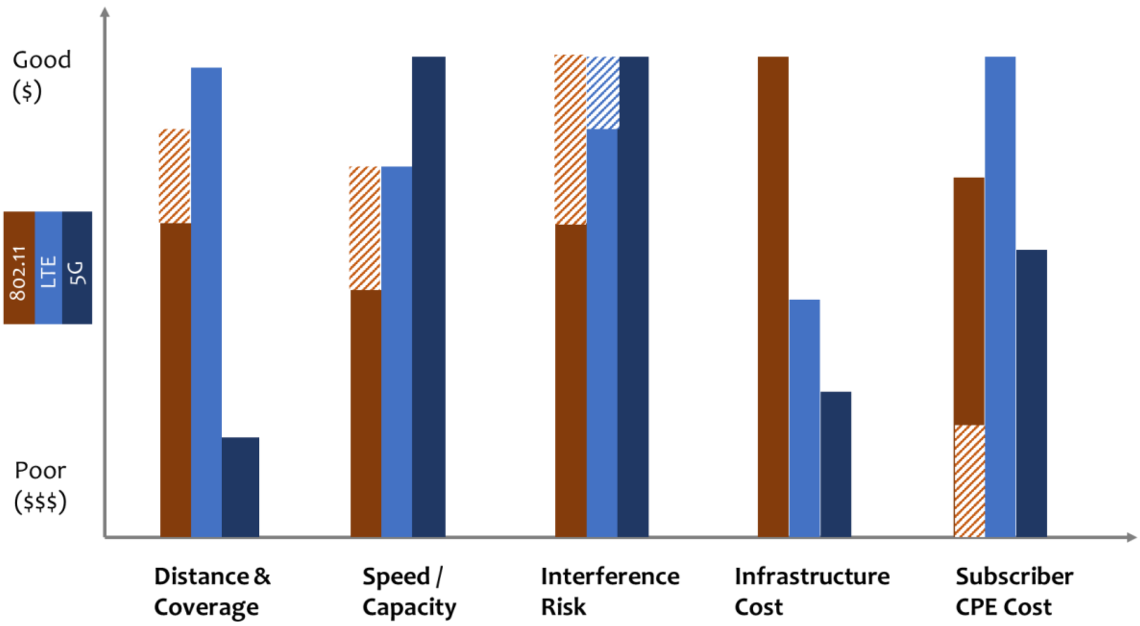
However, we can surmise relative assessments between the different types of fixed wireless technology based on general technology merits and representative product solutions in the marketplace.



Note: This is a high-level qualitative illustration. There is a wide variance in performance and cost of 802.11-based proprietary solutions. Actual product comparison should be made between each FWA solution under the same evaluation criteria (e.g., spectrum, market density, etc.) before making a 'buy' decision.

Source: Mobile Experts

Figure 12. Relative comparison of 802.11 (proprietary) vs. LTE vs. 5G FWA

Distance and Coverage

While the primary consideration of cell distance and coverage area is really a function of operating frequency spectrum and transmit power of base station AP and receiver sensitivity, we often attribute this to primary technology that we use in certain spectrum bands. At lower frequency bands, the ability for the radio signal to penetrate foliage and building structures gets better. LTE fixed wireless systems have better range and coverage and perform better in near and non-line-of-sight (NLOS) conditions than 802.11-based systems. LTE at 2.5 or 3.5 GHz under higher transmit power conditions works better than a typical 802.11-based system in the 5 GHz band. Meanwhile, 5G fixed solutions operating in the millimeter wave bands are small cell deployments with limited range and coverage area.

Speed and Throughput Capacity

The primary driver of throughput capacity and user speed is spectrum bandwidth, and the ability of underlying technology to ensure optimal throughput capacity under interference conditions. Operating in licensed spectrum bands ensures the best

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result since the system does not have to contend with possible interference risks. With 5G fixed operating in the licensed millimeter wave bands with abundant channel bandwidth, it offers the best throughput capacity and user speeds. While LTE fixed systems, operating in licensed bands, offer better performance in user speeds in nLOS and NLOS conditions, some proprietary solutions like Cambium PMP 450 claim better sector capacity and subscriber bandwidth than standards-based LTE systems. In the Cambium PMP 450 case, it has implemented MU-MIMO to achieve higher spectral efficiency.

Interference Risk

Interference risk is a function of operating frequency band, more specifically whether the operating band is licensed vs. unlicensed. If an operator can afford to use a licensed frequency band, then there is no issue since the license inherently protects the licensee from improper use of the channel by others. In reality, many fixed wireless operators rely on unlicensed bands and mitigating interference is the difference between having a successful broadband business or not having one! With LTE often associated with licensed bands, it is considered less prone to interference risk. With LTE use in unlicensed bands (e.g., LAA and MulteFire) becoming more popular, however, it is not 100% guaranteed from interference risk. While there is a huge variance in product performance concerning interference mitigation among proprietary solutions, some proprietary solutions claim better interference mitigation through fast beamforming and steering. While this may be true today, we expect the LTE and 5G certainly to have comparable or possibly better features in this regard.

Infrastructure and Subscriber CPE Cost

With a long history of serving the price-sensitive WISP market, the 802.11-based/proprietary solutions are less expensive than traditional LTE macro base stations. We have seen figures that are 2-3x cheaper in overall "tower" cost (i.e., a total buildout cost including equipment and construction) with 802.11-based vs. LTE gear. With the small cell market ramping up, we have seen price-competitive LTE gears from Chinese vendors that look to shake up this market. Meanwhile, the 5G fixed wireless gear is much higher than LTE today. As the 5G ecosystem matures, we expect the gear pricing to trend down similarly as we have seen in the 3GPP ecosystem.

While 802.11-based proprietary infrastructure is cheaper than LTE infrastructure, its CPE costs are higher than LTE fixed CPE's. The large LTE ecosystem includes over a billion smartphone shipments every year, so the LTE modem cost will continue its downward trend. The natural market forces of competition and global scale of LTE ecosystem will continue to provide a cost advantage for LTE CPE vs. 802.11-based proprietary CPEs.

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Spectrum is Paramount

Spectrum choices for fixed wireless access span across from sub-1 GHz to 70/80 GHz millimeter wave bands. This wide range of spectrum options come with caveats on distance reach and speed performance, AP-CPE cost tradeoffs, "$/GB" transport cost, architecture/deployment choices, core network requirements, and many other factors that impact on-going operations of delivering fixed wireless broadband service. One thing is clear. Spectrum is a key determinant of broadband service level (speed and quality), and cost at which that service is delivered.

Spectrum Band	Bandwidth	License Regime	Technology	Interference Risk
900 MHz (902 - 928)	26 MHz	Unlicensed	802.11 (proprietary)	High
2.4 GHz	~80 MHz	Unlicensed	802.11 (proprietary)	High
2.5 GHz	194 MHz	Licensed	3GPP (LTE)	Low
3.5 GHz (3.55 - 3.7)	150 MHz	Shared (CBRS)	3GPP (LTE), 802.11 (proprietary)	Medium (GAA)/ Low (PAL)
5 GHz (5.15 - 5.85)	580 MHz	Unlicensed	802.11 (proprietary), LTE (proprietary)	High
28 GHz	850 MHz	Licensed	802.11 (proprietary), 3GPP (5G)	Low
39 GHz (37 - 40)	3 GHz	Licensed (37GHz), Shared (39GHz)	3GPP (5G), 802.11 (proprietary)	Low
60 GHz (57 - 71)	14 GHz	Unlicensed	802.11 (WiGig)	Medium

Source: Mobile Experts

Figure 13. Spectrum options for fixed wireless access

Fixed wireless broadband service delivery over a licensed band is preferred of course since interference risk is inherently non-existent through the license, but this adds cost (spectrum and higher base station AP cost). Moreover, leveraging wide spectrum blocks such as the 5GHz and millimeter wave bands can provide very high throughput capacity, thus higher broadband speeds, but they are prone to interference risk in the case of using the 5GHz unlicensed band, and smaller coverage in the case of using the millimeter wave bands. Optimizing these tradeoffs along with assessing market demand and competition is key to success in fixed wireless access.

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900 MHz

The 900 MHz fixed wireless access systems are often found in far rural deployments where distance reach is paramount to making the business case work. Fixed wireless service providers primarily use this band to take advantage of the far-reaching RF propagation characteristics of this band. Due to limited spectrum in this band, however, the throughput capacity or speed offered to customers is limited to tens of Mbps at best. Operators sometimes need to consider interference mitigation strategy in case there are other unlicensed products (IoT devices, wireless microphones, etc) using the same band nearby. With the longer reach, the probability of interference is often higher.

2.4 GHz Unlicensed

Similar to the 900 MHz band, WISPs have used the 2.4 GHz band in the past to take advantage of a larger chunk of spectrum bandwidth in this band. With the popularity of Wi-Fi use indoors and out, the rising noise floor in this spectrum has made its usage problematic in the past. With most Wi-Fi indoor usage moving to the 5 GHz band, some operators are coming back to the 2.4 GHz band as the noise floor has come down somewhat to make this more useful. Like the 900 MHz band, this band is most often used in very rural areas to reach far away subscribers from a base station access point.

2.5 GHz Licensed

The 2.5 GHz band is comprised of Educational Broadband Service (EBS) and Broadband Radio Service (BRS) bands, totaling 194 MHz of usable spectrum within the 2495 – 2690 MHz band. With the FCC rule change in mid-2000's, the EBS and BRS licenses now allow two-way mobile and fixed data services. While Sprint holds the bulk of these licenses throughout the USA, some smaller operators use this band to provide fixed wireless services. Some are still utilizing WiMax-based technology in this band, but many operators now look to TD-LTE in utilizing this band.

3.5 GHz Shared (CBRS)

The *Citizen Broadband Radio Service* (CBRS) provides for shared spectrum use in the 3.5 GHz band. For the first time, dynamic spectrum sharing rules based on the three-tier licensing regime (as shown below) allows commercial use of the band while ensuring interference protection and uninterrupted use by the incumbent users (i.e., military radars and fixed satellite stations). Under the plan, a *Spectrum Access System* (SAS) maintains a database of all CBRS base stations and coordinates spectrum access among the incumbent and new commercial users. In the three-tier licensing structure, at least 80 MHz of spectrum are designated as *General Authorized Access* (GAA), or unlicensed use, and up to 70 MHz of *Priority Access License* (PAL) are planned to be auctioned off as licensed band shortly.

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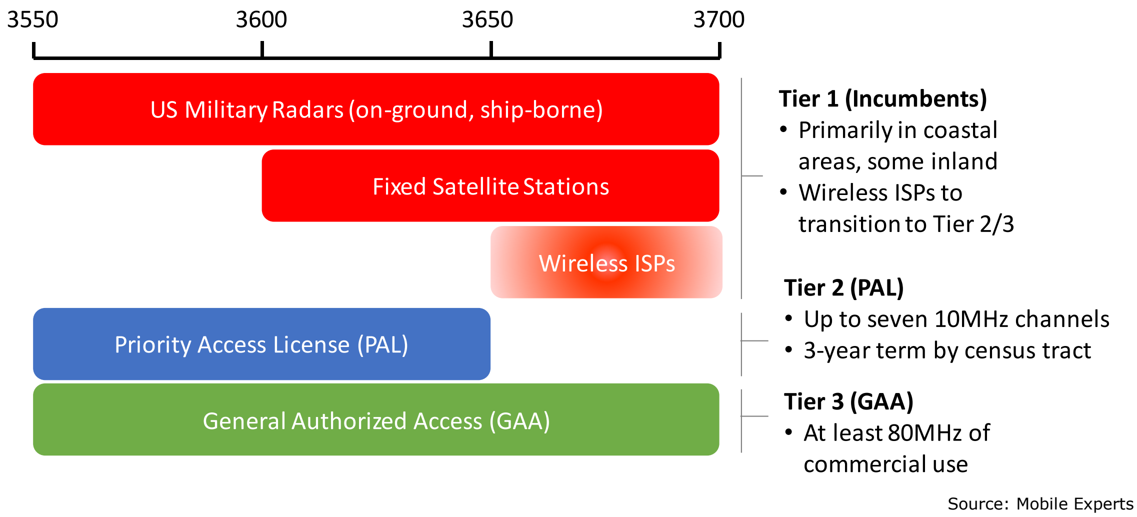

Figure 14. CBRS shared spectrum licensing framework

It should be noted that many WISPs currently use the 3.65 – 3.7 GHz band as temporary "incumbent" users for fixed wireless. By 2020, the use of this particular portion of the band will need to transition under the CBRS three-tier licensing regime.

3.7 – 4.2 GHz

With great interest in the 3.5 GHz CBRS band from many powerful mobile operators and cable providers, there is an effort to open up access to the 3.7 – 4.2 GHz band for FWA. This effort is being led by the Broadband Access Coalition, comprised of many notable companies and organizations in this field, including WISPA, Mimosa Networks, New America Foundation, Rise Broadband, Cincinnati Bell, and others. Moreover, other major companies, including Frontier, Windstream, Starry, Google, and Microsoft are backing this lobbying effort to open up 500 MHz of additional spectrum adjacent to the CBRS band. The FCC will need to decide whether this band should be licensed for mobile, shared (as with CBRS), or structured in another way. Outside of the USA, many governments are looking at this band for potential 5G services. So far, the direction of this band in the USA is unclear.

5 GHz Unlicensed

For many WISPs, the 5 GHz band has been the "workhorse" of delivering fixed wireless broadband access with relatively large amounts of bandwidths available across several different frequency band ranges with different usage requirements. For fixed wireless application, many WISPs use "U-NII-2-extended" and "U-NII-3" bands for different reasons. With dynamic frequency selection (DFS), or radar avoidance, requirement, many common Wi-Fi access points typically do not use the "U-NII-2-extended" band. Thus, it is relatively "pristine" unlicensed spectrum upon which to deliver fixed wireless access, especially for operators targeting denser

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suburban settings. Moreover, this particular band is considered a "worldwide" band as it is designated as unlicensed globally. Hence, it provides a greater market opportunity for vendors to address the global market. Unlike the U-NII-2-extended band, the U-NII-3 band provides a greater transmit power limit. Hence, this is popular among traditional WISPs looking to maximize reach, especially in rural areas where the business case mandates a maximal coverage.

Band	Freq. Range	Bandwidth	Max. transmit power	Max. EIRP
U-NII-1	5.15 – 5.25 GHz	100 MHz	50 mW	200 W
U-NII-2A	5.25 – 5.35 GHz	100 MHz	250 mW	1 W
U-NII-2B	5.35 – 5.47 GHz	120 MHz	Not used in unlicensed access	
U-NII-2 extended (*)	5.47 – 5.725 GHz	255 MHz	250 mW	
U-NII-3	5.725 – 5.85 GHz	125 MHz	1 W	200 W

Source: Mobile Experts

Figure 15. 5 GHz unlicensed U-NII band ranges

28-39 GHz Licensed

The 28-39 GHz band is often perceived as the 5G band, especially in the United States where operators are competing to launch the first "5G" network. With recently acquired 28 and 39 GHz bands from XO and Straightpath, Verizon is looking to put these spectrum assets to work through 5G fixed wireless service. Although Verizon's initial fixed wireless service will leverage its homegrown 5GTF specification, the network is expected to be upgraded to 3GPP 5G NR fairly quickly. As the mobile ecosystem works towards enabling true mobile use of these high spectrum bands through massive MIMO and beamforming and beamtracking, some may deploy these spectrum assets towards fixed wireless access application in a similar manner as Verizon. Why not put a good spectrum asset to use when the underlying network infrastructure, in terms of small cells, sites, backhaul, etc. can be extended to mobile application when a handset ecosystem has had a chance to catch up.

The use of this millimeter wave band is not exclusively tied to 3GPP however. Starry has created a proprietary fixed wireless system based on a 802.11-based chipset solution from Marvell using the 37 GHz millimeter wave band. The company's selection of the 37 GHz band is strategic, in our opinion, as FCC is expected to license over 2 GHz of this spectrum sometime in late 2018 or 2019.

60 GHz Unlicensed

The 60 GHz unlicensed band provides tremendous amount of spectrum bandwidth. With a high oxygen attenuation in the 60 GHz band, the use of this band for fixed

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wireless is confined to short-reach distances, less than 300 meters. While this band has been used in point-to-point (PtP) context for many years, many vendors are developing point-to-multipoint (PtMP) systems to take advantage of the large swath of spectrum for high-speed broadband access in urban and suburban settings. Many vendors including Nokia, Siklu, Intracom and many others provide PtMP solutions operating in the 60 GHz band. Because of high attenuation and shorter reach, the 60 GHz PtMP solutions will require outdoor antenna deployment and high-gain beamforming capability to enable fast installation and activation.

'Tower' vs. 'Micro Hub' Architectures

Fixed wireless operators can target varying market density environments with different deployment architectures to minimize the cost per bit economics. As noted earlier, major cost elements in a fixed wireless access system include:

- Base station access point (AP)
- Customer premise equipment (CPE), or subscriber modules
- Spectrum (if licensed band is utilized; $0 for unlicensed)
- Site cost ("tower" lease)
- Backhaul (fiber or wireless backhaul link cost)

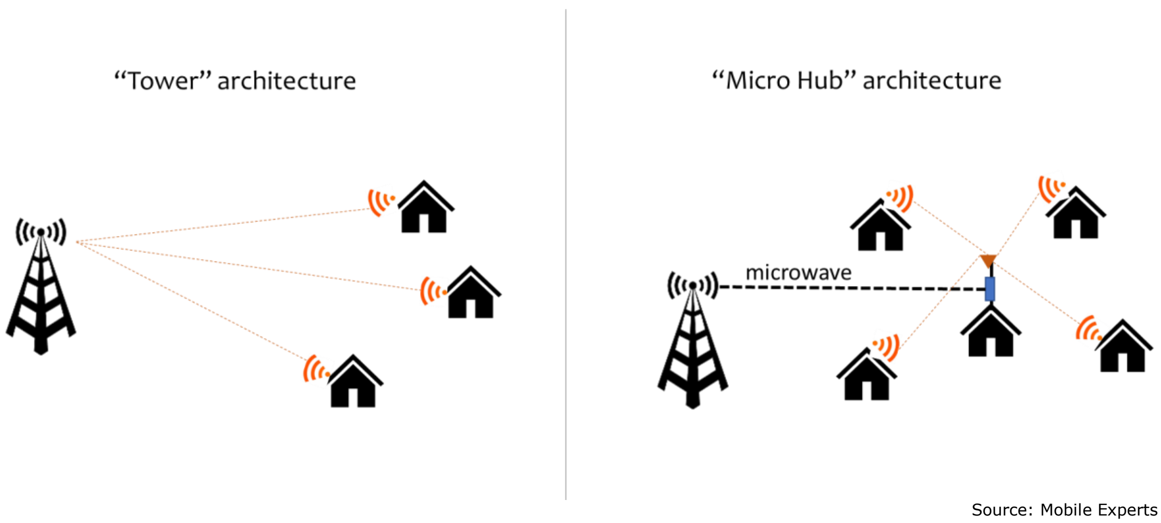

Figure 16. "Tower" vs. "Micro Hub" architecture

Most fixed wireless systems in rural markets employ the traditional "tower" architecture whereby a PtMP radio on a tower serves multiple subscriber radios. While this makes sense in rural markets where operators look to optimize for coverage to pass as many homes and businesses in sparsely populated areas, the "tower" architecture becomes uneconomical in denser suburban or urban settings. In order to provide competitive high-speed broadband service in denser markets (50-

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100 Mbps in the USA), fixed wireless networks need to be densified. The higher number of sites, if they can even be acquired expeditiously, and associated backhaul, adds cost. To address this, some operators and vendors are advocating what we call "micro hub" architecture (named after the "hub and spoke" concept).

In the "micro hub" architecture, the placement of PtMP radio happens at one of the homes in a neighborhood (under a reciprocal commercial arrangement whereby the "hub" homeowner gets free broadband service in lieu of placing the PtMP radio and antenna on his/her rooftop) instead of on a tower. The "hub" home would be connected wirelessly to a tower that aggregates backhaul traffic from multiple hubs, which is then fed up to an Internet PoP. At each "hub" home, a PtMP radio could serve a limited number of subscribers using unlicensed spectrum with either 802.11-based or LTE fixed technology.

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5. ECONOMICS OF FIXED WIRELESS ACCESS

Fixed wireless economics, driven by technology advancements and spectrum availability, continues to advance, offering higher speed broadband capabilities at lower costs. Both 802.11-based and 3GPP-based (LTE and 5G) fixed wireless technologies continue to lower the "cost per GB" unit economics opening new market opportunities and solutions to a wide array of service providers ranging from enterprising WISPs and OTT competitive carriers to large incumbent operators. Moreover, new spectrum choices in both unlicensed and licensed bands--ranging from sub-1 GHz to the millimeter wave bands--are bringing a wide array of fixed wireless options to both rural and urban markets.

Unit Economics of "Cost to Pass" and "Cost to Connect"

In fixed wireless, numerous levers control the overall network cost. Such factors as spectrum cost, cell range, market density, base station and CPE costs, along with other operational expenses like site and backhaul costs, all impact the overall network cost. The fixed wireless unit economics, like other broadband technologies, is ultimately driven by the "cost to pass" and the "cost to connect" a subscriber. In fixed wireless, the "cost to pass" is driven by base station, spectrum cost (in case of licensed band use), site lease, backhaul, and power. Meanwhile, the "cost to connect" is primarily driven by customer premise equipment (CPE) or subscriber radio unit, and a "truck roll" for professional installation of CPE, radio tuning, and service activation.

A unit cost curve of a fixed wireless system, on monthly basis, is shown below.[9] At lower market penetration, the overall network cost curve is dominated by the "cost to pass" components since there is not enough subscribers on the network to "spread" the initial capital expenditure of base station and associated site costs. As the market penetration increases, i.e., as more subscribers are added to the network, the overall network cost is primarily driven by the "cost to connect" components, i.e., CPE and installation costs.

[9] The illustrated network cost curve depicts a LTE fixed wireless system with a $40K LTE macro base station with a cell range of 1.5 miles in a suburban environment of ~1000 homes per square mile. The model assumes $120 LTE fixed CPE.

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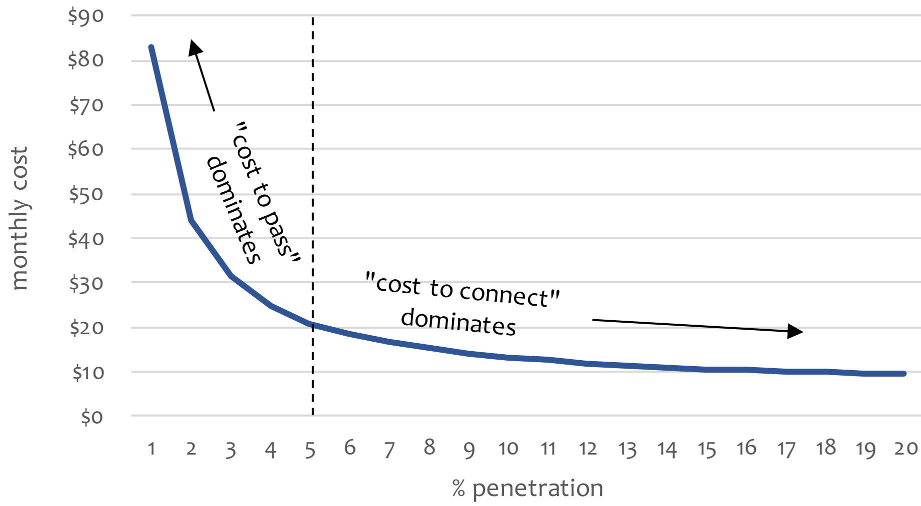

Source: Mobile Experts

Figure 17. Cost optimization against expected market penetration

What this implies is that if an operator believes that it won't achieve high market penetration (for competitive or other reasons), then it would likely focus on a fixed wireless system that offers lowest possible "cost to pass." In other words, the operator would try to lower base station and other site costs. On the other hand, if the operator believes that it can achieve high market penetration, it would likely focus on the "cost to connect" components, i.e., CPE and installation/activation costs. Ultimately, a service provider is constantly optimizing network cost against market demand to make sure the service can be delivered at a profit.

Fixed Wireless Cost Advantage over Wireline

One of the key aspects of fixed wireless economics is that it provides a cost advantage over a typical wireline technology like FTTH. More importantly, it provides a quick time to market advantage. Standing up a fixed wireless base station site to cover a wide geographic coverage is certainly a lot quicker than trenching fiber or coaxial cable through neighborhoods.

The figure below illustrates the cost advantage of fixed wireless over a typical wireline technology such as fiber. Specifically, the figure compares the total cost to connect a subscriber through a couple of fixed wireless variants vs. fiber to the home (FTTH). The first two bars in the below figure represents the total cost to pass and connect a subscriber through LTE and 802.11-based fixed wireless solutions in a

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typical rural environment[10] while the next two bars represents 5G fixed and 802.11-based millimeter wave system in suburban/urban setting[11]. Lastly, the right-most bar shows a FTTH cost for a typical suburban/urban environment in the USA. It should be noted that FTTH cost is highly dependent on market density and region. In sparsely populated locations or high-cost regions, the FTTH cost can be almost $3000 per line.

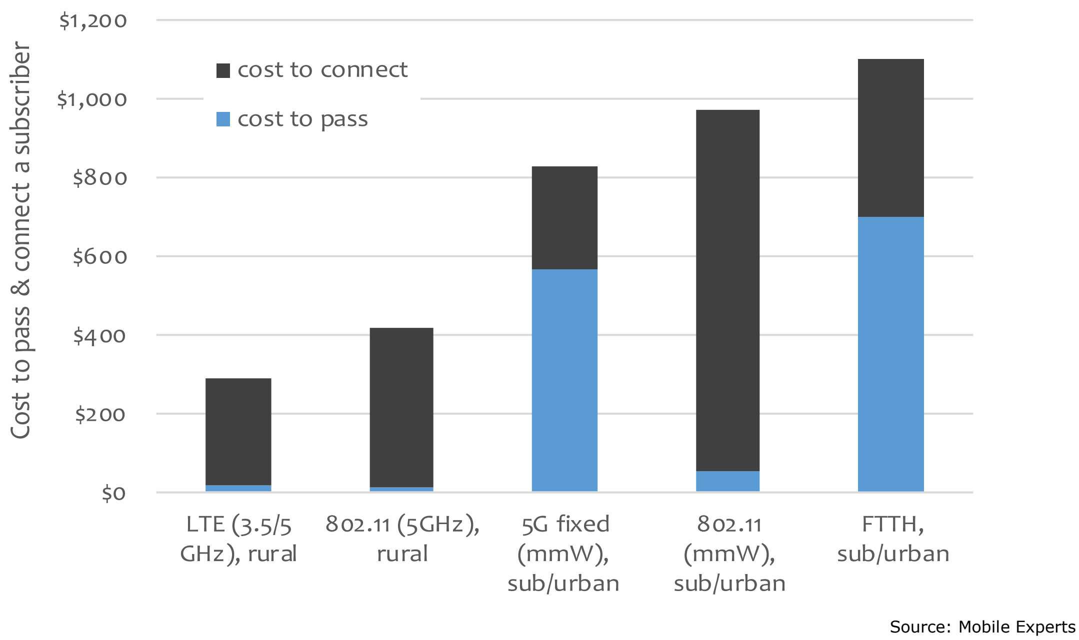

Figure 18. Cost to pass and connect a subscriber via FWA vs. FTTH

Economic Tradeoff of 3GPP-based vs. 802.11-based FWA

One of the trends in the rural WISP market is the increasing use of LTE fixed solutions. Despite a general notion that LTE systems require licensed spectrum bands, several companies offer LTE fixed wireless use in the unlicensed bands, such as the 5 GHz band, for those who do not have an access to licensed spectrum. While not officially MulteFire certified per se, solutions from several Chinese vendors including ZTE and Baicells offer LTE radio gear designed for the unlicensed 5GHz band.

[10] A fixed wireless cell distance can range up to 3-4 miles in rural deployments to maximize the number of locations in a given coverage area. Our model assumes a rural market density as ~500 homes per square mile.
[11] We modeled the 5G fixed wireless costs based on our current understanding about Verizon's upcoming 5G home broadband service. We believe the average cell distance would be 300 meters, with conservative cost estimates for site lease and backhaul, and a CPE cost of ~$200.

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Upfront capital expenditure costs of installing an "LTE" base station tower vs. 802.11-based "Wi-Fi" tower can be significant for enterprising WISPs with limited capital expenditure budget. Mobile Experts estimates that the total upfront capital expenditure, including one-time construction costs, to build out an "LTE" tower can cost about $60,000 today. In contrast, this cost for a "Wi-Fi" base station tower is about $24,000 as shown below.

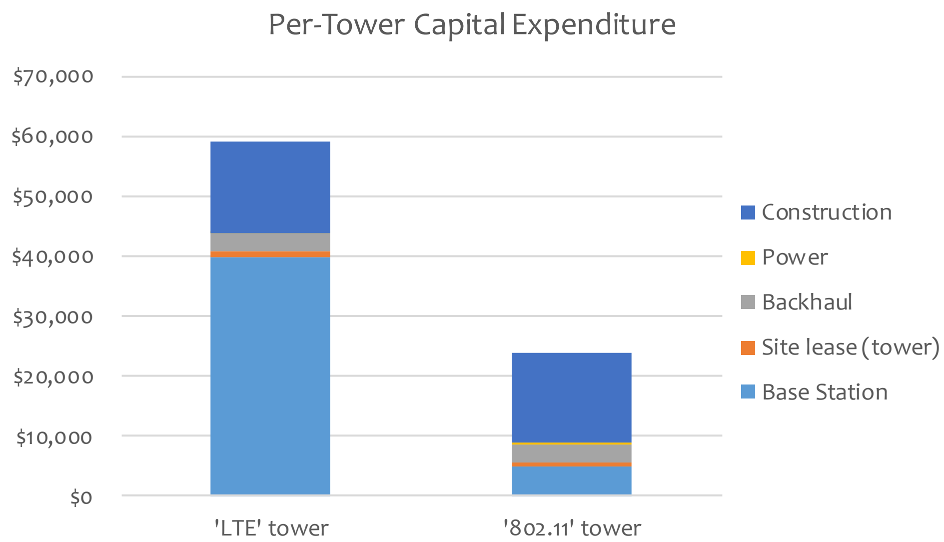

Figure 19. Upfront cost to build out an "LTE" vs. (802.11-based) "Wi-Fi" tower

The meaningful cost difference in opting for a 3GPP-based "LTE" tower vs. an 802.11-based "Wi-Fi" tower stems from the fact that a typical LTE macro base station can cost almost ten times higher than a 802.11-based fixed wireless access base station such as Cambium PMP 450. Besides the base station and construction costs, other major items include backhaul and site lease. Our cost model assumes a blended cost of fiber (a very small portion) and a pair of point-to-point radios for wireless backhaul (~$3000) commonly used in rural deployments. Also, our model assumes a blended cost of traditional and non-traditional "tower" site lease cost of ~$750.[12] So, the question is: why would an operator seek LTE fixed wireless solution over 802.11-based solution, when the upfront capital investment for an LTE system can be meaningfully higher than an 802.11-based fixed wireless system?

Despite the higher upfront capital outlay, some operators are choosing 3GPP-based LTE fixed wireless solution for strategic and economic reasons. Strategically, the

[12] A blended rural tower site lease cost is calculated as 1/3 of traditional cell tower cost of $1200 plus 2/3 of non-traditional "tower" (e.g., water tower, roof top, etc.) cost of $500. In some instances, the non-traditional tower cost can be much lower depending on local market demand for high-speed broadband services and a willingness to forgo or subsidize the site lease cost to enable such services.

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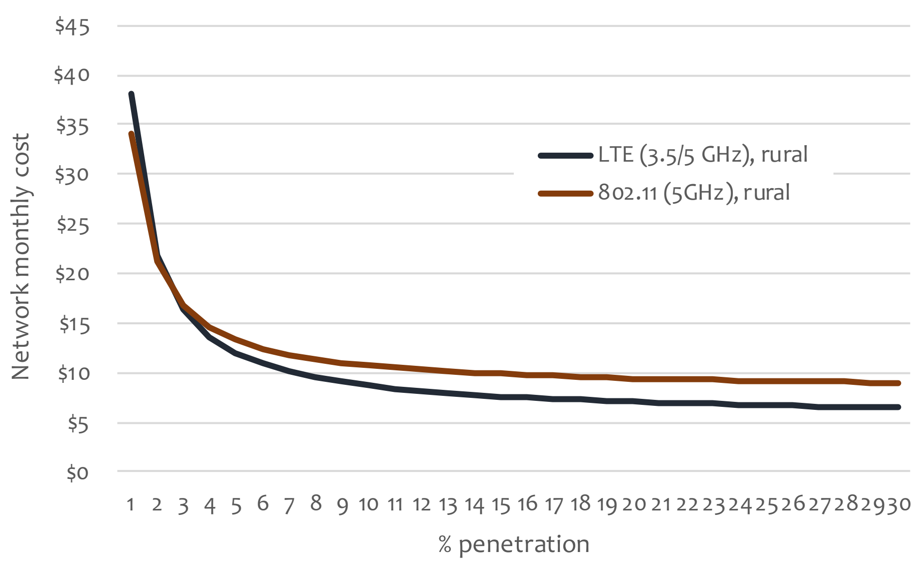
3GPP-based LTE radio gear is perceived to provide performance and scale advantages over 802.11-based proprietary solutions. Some operators state that LTE gear typically has a longer lifetime on towers, thus provide a better network investment over a longer time horizon than some 802.11-based gears. Moreover, these operators point out that a larger LTE ecosystem provides a robust technology roadmap and a strategic assurance that there will be multiple vendors who can supply the necessary network infrastructure.

Besides the strategic reasons for LTE fixed gear, some operators are driven by economics in choosing LTE over 802.11-based proprietary solutions. The figure below illustrates the overall network costs of an LTE vs. 802.11-based fixed wireless system in a rural setting.[13] It shows that while 802.11-based system is cheaper at very low market penetration rates (below 3% in the figure below), the LTE system is cheaper in most cases. This is because LTE-based CPEs are cheaper than 802.11-based proprietary systems. While there are less expensive 802.11-based CPEs in the market, like Ubiquiti for example, some larger operators see a strategic value in standard-based LTE solutions that presumably offer interoperable CPEs from multiple vendors, not tied down to vendor-specific CPE's associated with base station gear.



Source: Mobile Experts

Figure 20. 802.11-based vs. LTE Fixed network costs in rural deployment

The choice between LTE vs. 802.11-based fixed wireless access system essentially comes down to a tradeoff between higher upfront CapEx cost vs. less expensive CPEs. For larger operators who have lots of subscribers on their networks already, or

[13] The "rural" cost model assumes a fixed wireless base station with a 3-4 mile cell range covering a market density of ~500 homes per square mile. For LTE, $40K macro base station and $120 CPE costs are assumed. For 802.11-based system, we assume $4900 for a 4-sector base station and $255 for CPE.

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expect to achieve high market penetration, may see the higher upfront capital expenditure as a necessary investment towards attaining lower network cost structure (i.e., cheaper LTE CPEs). For enterprising service providers with limited "start-up" capital, 802.11-based solutions offer lower-cost base station gears to start, but typically have higher-cost CPEs as compared to LTE ecosystem.

Fixed Wireless Economics of Distance vs. Speed

One of the fundamental tradeoffs in broadband economics is the tradeoff between distance vs. speed. As the distance increases, speed decreases. In fixed wireless access, a cell's range is an artificial limitation of what a particular technology can deliver, in terms of network capacity, against offered or advertised speed to subscribers. It is a balancing act of maximizing distance to cover as many potential subscribers as possible while providing high enough "Mbps" speed to subscribers to make the broadband service compelling.

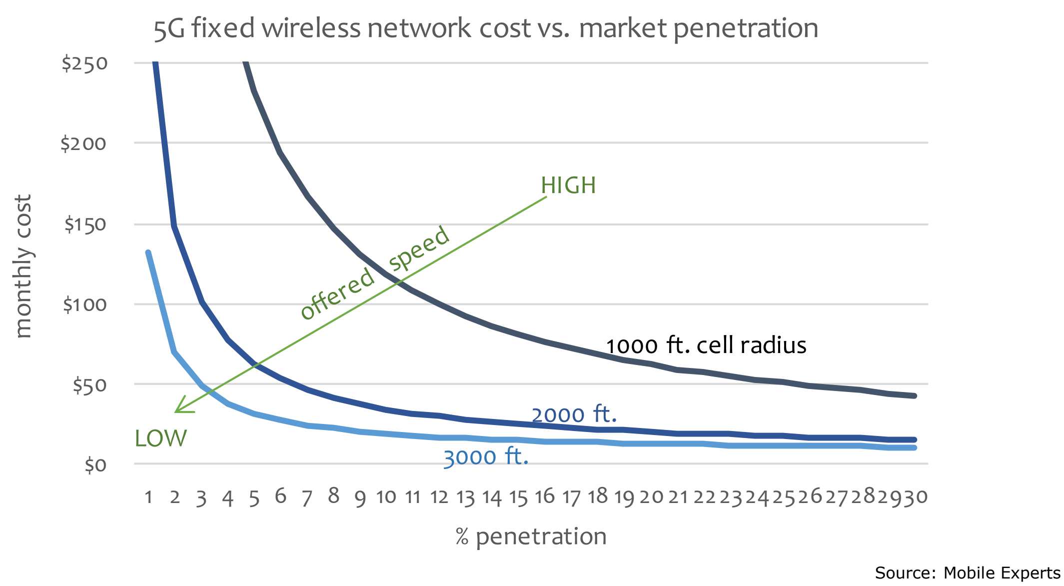

Figure 21. Fixed wireless economics of speed vs. reach

As illustrated in the 5G fixed wireless network cost curves above[14], there is an economic tradeoff between offering higher speed at a short distance vs. presumably slower speed offer at a longer distance. Assuming a "1 Gbps" speed offer can be made at the 1000 ft. cell radius case for $100 with a 50% margin expectation[15], the

[14] The "5G fixed" cost model assumes the market density of 500 homes per square km (or ~1300 homes per square mile).

[15] Based on Verizon's preliminary "5G home broadband" pre-commerical results showing 1 Gbps median speed at 1000 ft. radius, and some gigabit service offering at above $100 in the marketplace, we believe that this is a reasonable offer in the marketplace.

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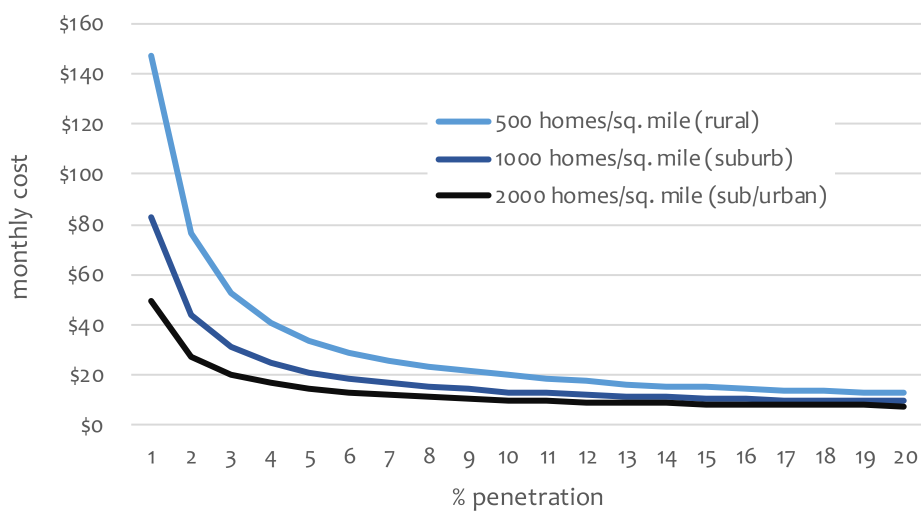
network cost model implies that an operator needs to achieve 25% market penetration. Similarly, assuming an operator can deliver "200 Mbps" speed at 2000 ft. cell radius for $70 with a 50% margin expectation, then the model implies that the operator needs to achieve about 10% market penetration. Depending on market demand, we would expect an operator to optimize this "cell distance-speed" tradeoff against network cost structure to deliver fixed wireless service at a profit.

Favorable Economics of Dense Markets

Fixed wireless access, or more broadly broadband, economics is heavily dependent on market density. Deploying a broadband network in heavily dense market provides a better economics since the "cost to pass" goes down as more homes and business locations can be addressed with a fixed network deployment. As an illustration, the below figure delineates a total network cost, including the "cost to pass" and the "cost to connect," across three different scenarios of market density.



Source: Mobile Experts

Figure 22. LTE fixed wireless network cost vs. market density

The fixed wireless access economics is more favorable for a denser market environment (note the lower network cost curve for the '2000 homes per square mile' sub/urban case vs. the '500 homes per square mile' rural case). Assuming a cost target of $20 (to have enough margin for a $50 offer to make the business case profitable), the figure shows that the fixed wireless service can reach a breakeven at around 10-11% market penetration for the rural case (~500 homes per square mile). In other words, a service provider needs to sign up 50-55 subscribers within the coverage area to achieve profitability! For the sub/urban setting, this "breakeven" market penetration is even lower -- just 4%! While this seemingly low penetration rate seems easy to reach, the 4% market penetration translates to 80 subscribers. In a

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competitive market with strong broadband alternatives like cable and fiber from incumbent players, even signing up 80 subscribers may not such an easy feat.

The fixed wireless economics favors deploying in heavily dense markets, as the network cost curve is lower. However, heavily penetrated cable and fiber footprints in dense urban and older suburban markets, and the market competition posed from incumbent players make fixed wireless deployment in denser suburban and urban markets non-straightforward. While fixed wireless access provides an economical means to provide "tens of Mbps" broadband services in rural and underserved markets, "hundreds of Mbps" and "gigabit" fixed wireless service opportunity in urban settings requires a careful assessment of speed offering, demand, and competitive response from incumbent players in the region.

Cost Comparison of 802.11-based vs. LTE vs. 5G Fixed

To evaluate comparative economics of 802.11-based vs. 3GPP-based fixed wireless systems, it is important to make a 'like-for-like' comparison. Speed offer, cell range, market density, and other factors all influence the network cost structure depending on what an operator is trying to optimize. For example, an operator may look to maximize coverage over speed offering for a given market density while another may look to provide high-speed offer over relatively shorter cell distance. To make a fair comparison, we have modeled two use cases: 1) 802.11 vs. LTE in a rural market; and, 2) 802.11 vs. 5G using millimeter wave in an urban market.

The 802.11 vs. LTE fixed wireless network costs for a rural market scenario is shown in Figure 3. Here, we have modeled an equivalent cell distance of 5 km (3-4 miles) for both 802.11-based and LTE base station for a market density of 200 homes per square km (500 homes per square mile). As shown, the two technologies share similar cost profile with the 802.11-based system having better economics at lower market penetration while LTE fixed system providing slightly better economics (~$2 lower monthly cost) over 802.11-based system. The lower LTE cost structure stems from the fact that LTE CPEs are cheaper than proprietary 802.11-based CPEs which are vendor-specific. Meanwhile, the standard-based LTE CPEs can be presumably sourced from multiple vendors thus providing scale advantages and lower cost.

The 802.11-based vs. 5G fixed wireless network costs for an urban setting (2000 homes per square mile) is shown below. Here, we have modeled our 5G fixed case based on our understanding of Verizon's "5G home broadband" service. Meanwhile, we have modeled our 802.11-based (millimeter wave) system based on our understanding of the Starry system in Boston. Since the two systems are optimized for different goals, we have also modeled the "5G (500m)" case to showcase a 5G fixed system assuming that Verizon's 5G fixed service is extended to a 500m cell radius (vs. 300m case for Verizon's baseline case) for "200 Mbps" speed offer as is

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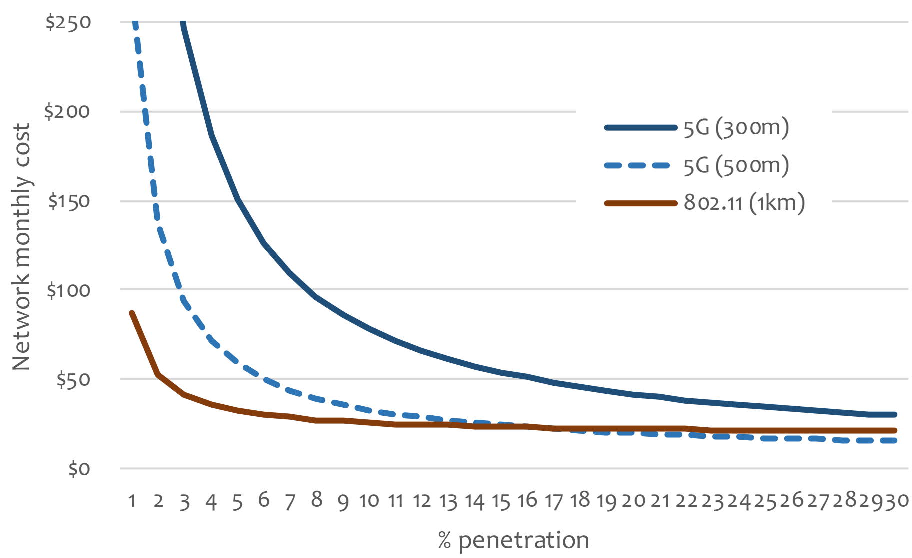
the case with the Starry system. While the current "5G" fixed wireless systems from both 802.11-based and 3GPP-based systems offer similar network cost structures, we believe that 5G fixed can drive its cost structure further down as the 5G mobile ecosystem scales up (i.e., as the high-volume smartphone ecosystem adopt millimeter wave band support). We expect this to happen around 2020-2021.



Source: Mobile Experts

Figure 23. 802.11-based vs. 5G Fixed network costs in urban deployment

Economic Optimization – Rural vs. Urban

Based on the economics of fixed wireless and observed market activities, we can draw a few conclusions:

1. A start-up fixed wireless operator may choose to optimize for the "cost to pass" (i.e., look for lower base station, spectrum, and site costs) before it can gain scale (i.e., higher market penetration);

2. This behavior is commonplace in rural markets where operators are primarily focusing on coverage. Inexpensive infrastructure buildout using unlicensed 802.11-based proprietary solutions is common since interference risk from using unlicensed spectrum is low in sparsely populated rural markets;

3. A large-scale or an incumbent fixed wireless operator is likely to be more concerned with the "cost to connect" (i.e., CPE cost). In this case, lowering the CPE cost is likely more important than the initial infrastructure cost. This economic consideration is driving some larger WISPs to transition to LTE fixed systems to take advantage of lower-cost CPEs. Moreover, they like the 'safety

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net' of longer-term 3GPP technology roadmap with multiple vendors behind the standards-based ecosystem;

4. Fixed wireless is a natural fit in underserved rural markets where the competition is relatively benign, and there is a pent-up demand for a high-speed broadband service; and,

5. Fixed wireless for urban market will require higher speed offerings than the ones typically found in rural/suburban markets. The wider spectrum bandwidth available in the millimeter wave bands is a natural fit, but the economics of extending cell range needs a careful tradeoff consideration against higher complexity, hence cost, of a CPE. Starry's high-cost CPE system appears to be focusing on extending cell range to maximize market opportunity of MDUs first.

6. Meanwhile, Verizon's 5G fixed architecture uses the small cell model (~300m cell range) which appears to be optimizing for throughput performance (~1 Gbps) rather than coverage. While the smaller cell deployment model is more expensive to build out, we believe Verizon's motivation is fundamentally different than a startup like Starry. We believe Verizon's primary goal is to eventually transition their 5G fixed wireless infrastructure to mobile use. Verizon's 5G investment is mobile-first, while a startup like Starry is fixed-first.

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6. Fixed Wireless Access Equipment Outlook

The growing fixed wireless access (FWA) equipment market can be segmented into 802.11-based solutions and 3GPP-based LTE and 5G solutions. The 802.11-based proprietary fixed wireless solutions from historical vendors in the space such as Cambium, Ubiquiti, and others, provide a range of point-to-point (PtP) and point-to-multipoint (PtMP) radio products for wireless backhaul and access systems. While these 802.11-based solutions remain a bedrock of many fixed wireless systems today, 3GPP-based LTE, and pre/5G solutions in a few select markets are expected to grow in count as larger operators target rural and denser markets with multi-vendor solution set base on standards-based solutions.

Fixed Wireless Access Equipment Forecast by Technology

While today's fixed wireless access (FWA) market is dominated by unlicensed 802.11-based proprietary systems, Mobile Experts is forecasting a growing adoption of standards-based LTE systems for fixed wireless. We believe this adoption will primarily come from larger mobile/telco operators, and possibly cable operators. These major telecom players will be driven by government programs (e.g., CAF II, National Broadband Plans) and internal motivation to extend their primary wireline footprints with alternative broadband network with standards-based technology. Also, larger WISPs, who are drawn to the standards-based LTE ecosystem to lower CPE cost, will increasingly adopt LTE as they go through infrastructure refresh cycles and more cost-effective LTE fixed solutions come available.

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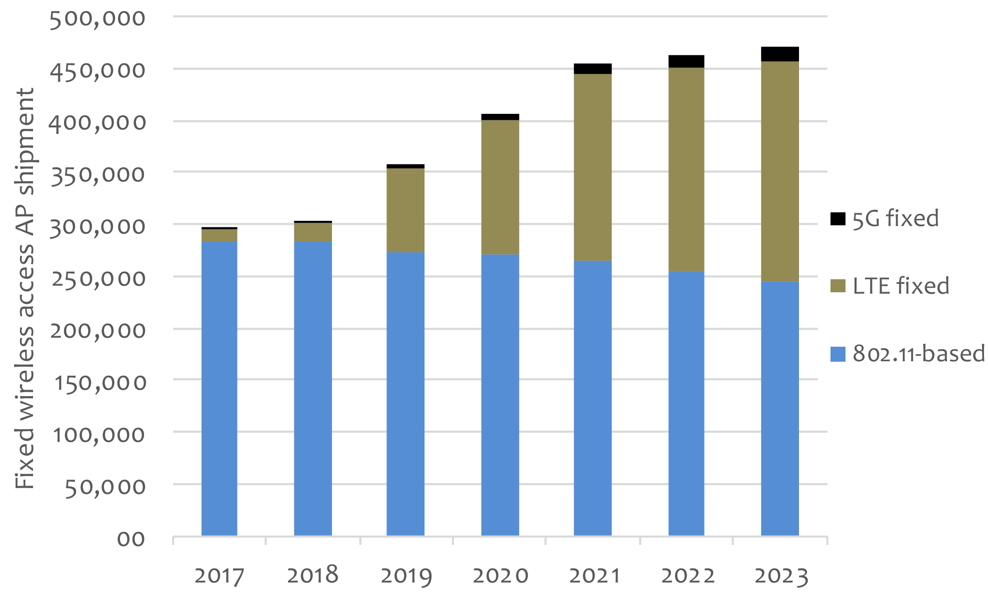

Notes: 1) "LTE fixed" AP shipments reflect new base stations specifically dedicated for the fixed wireless application.
2) Existing mobile LTE base stations shared across both mobile, and fixed broadband access are not counted.

Source: Mobile Experts

Chart 2: Fixed wireless access AP shipment by technology, 2017-2023

Mobile Experts forecasts the 802.11-based proprietary AP shipments to gradually decline at -2% CAGR during the forecast period (2018 - 2023) while the 3GPP-based LTE AP's dedicated for fixed wireless application will grow at around 60% from tens of thousands of base station AP's to over 200,000 in 2023. Our forecast assumes that many of integrated mobile/telco operators will adopt LTE fixed wireless access solutions to leverage their existing LTE core infrastructure. If they decide to separate mobile vs. fixed broadband services on separate infrastructures, then our forecast can change quite significantly. For 5G fixed, we currently expect a modest growth in AP unit shipments as we believe 5G fixed market opportunity is somewhat limited by heavy penetration of competing wireline FTTH and Cable solutions in dense markets. In developing regions, "gigabit" market opportunity is mostly limited to enterprise market which is already addressed through proprietary PtP and PtMP solutions.

It should be carefully noted that the LTE AP shipments shown above only reflect "dedicated" LTE base station AP's specifically targeted for fixed wireless access. We believe many mobile/telco operators are leveraging their existing LTE infrastructure on a "shared" basis to serve both mobile and fixed users. If we were to count the "shared" LTE base stations in the mix, the LTE AP shipment will be much higher.

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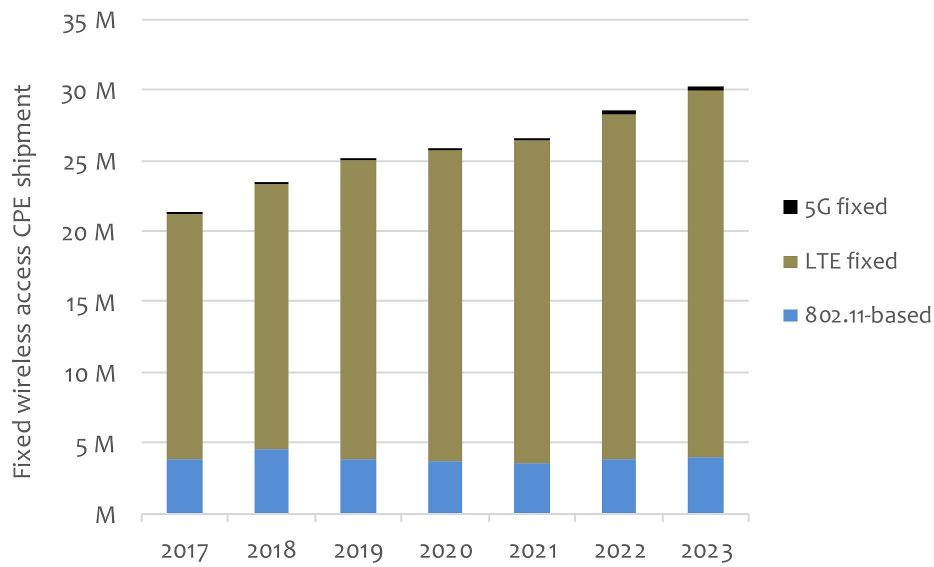

Source: Mobile Experts

Chart 3: Fixed wireless access CPE shipment by technology, 2017-2023

The fixed wireless subscriber CPE shipments are forecasted to grow at mid-single digits during the forecast period. Most of the growth is expected to come from the LTE CPE shipments while the 802.11-based proprietary CPE unit shipment is expected to remain muted, hovering around 4M units annually. The LTE fixed CPE shipment is expected to grow at 7% CAGR from 2017 to 2023, rising to 26M in 2023. In comparison, the 5G fixed CPE shipment is expected to be relatively small, growing from less than 10K units in 2018 to roughly 300K units in 2023.

802.11-based Fixed Wireless Access Equipment Forecast

As noted earlier, the 802.11-based fixed wireless AP units mostly operate in unlicensed bands (to mostly target WISPs who don't have licensed spectrum). With relative advantages of large chunks of channel bandwidth, decent RF propagation, and less prone for interference in target markets, the 5GHz band, more specifically the 5.4 and 5.8 GHz bands, are pretty popular. While we expect some 900 MHz, 2.4 GHz, and 3.65 GHz access points to ship during our forecast period, we expect the total number of units to be small. The 5GHz units will dominate the 802.11-based AP shipments. Meanwhile, we expect 60 GHz PtP and PtMP radios for fixed wireless access to grow modestly, but we expect many of those radios to be used for short-distance backhaul in "micro hub" architecture. The actual fixed wireless access to subscriber homes and businesses will be niche as they will predominantly be used to offer very high-speed links either as PtP or PtMP from a "hub" site. Similarly, the proprietary 28-39 GHz millimeter wave PtMP products will be targeted mostly for enterprise segment to offer "hundreds of Mbps" or "gigabit" service to high-demand markets.

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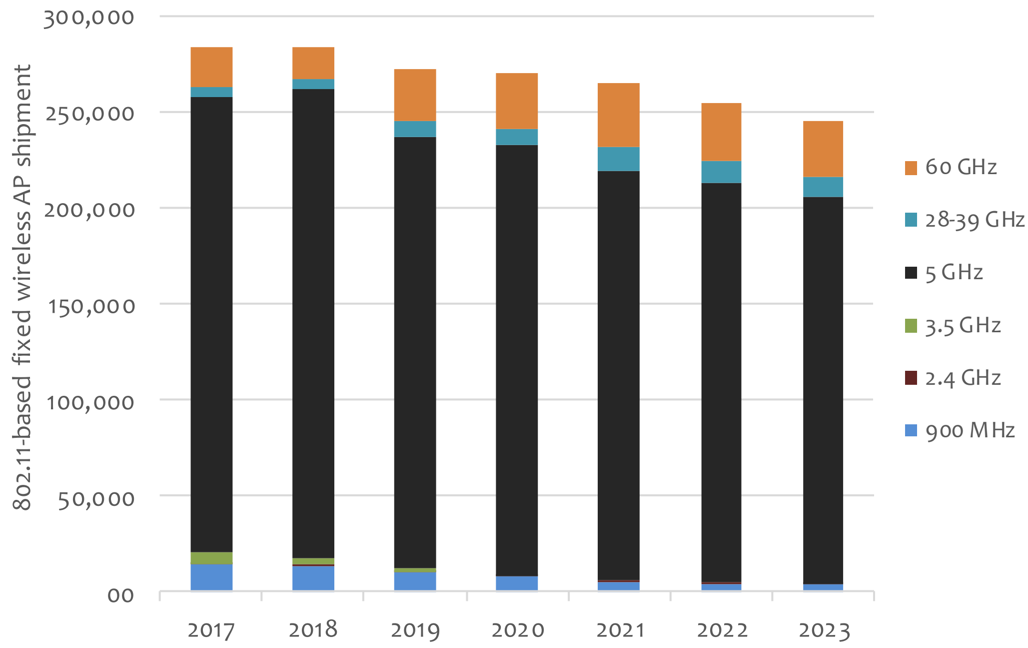

Source: Mobile Experts

Chart 4: 802.11-based fixed wireless access AP shipment by freq. band, 2017-2023

LTE Fixed Equipment Forecast

The "dedicated" LTE fixed wireless base station AP shipment will target new spectrum opportunity in the 3.5 GHz. The CBRS band allocation in the USA will drive major telecom operators and WISPs to tap this "new" spectrum for fixed wireless access. The ramp is expected to start in earnest in early 2019 as the underlying CBRS ecosystem or SAS and vendor communities finish their early trials and wait for FCC to give a "green light." Globally, the 3.5 GHz band is being opened up as a part of "5G" spectrum allocation. We expect some operators to leverage the large chunks of spectrum bandwidth for fixed wireless application. Also, we expect some shipment of LTE for 5GHz unlicensed band to be deployed among some WISPs as they look to harness network scalability and lower CPE cost structure of LTE ecosystem.

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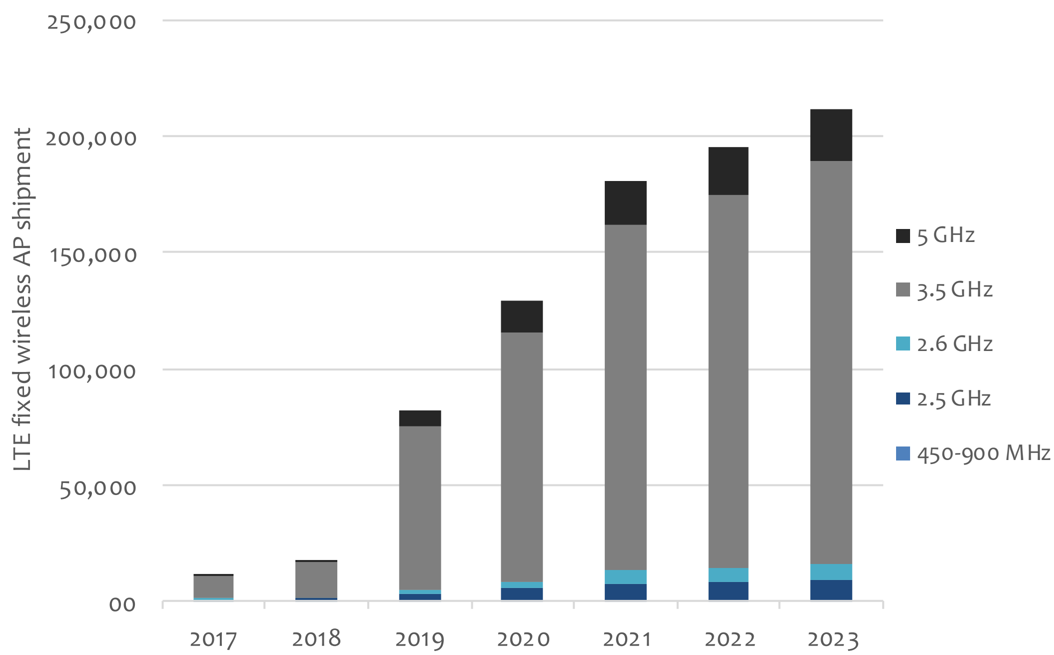

Source: Mobile Experts

Chart 5: LTE fixed wireless access AP shipment by freq. band, 2017-2023

5G Fixed Equipment Forecast

Our 5G fixed wireless AP shipment forecast is primarily driven by Verizon's 5G fixed commercial deployment plan. We expect a few thousand AP shipment in 2018 for Verizon's "3-5 market" commercial launch in the second half of 2018. While Verizon touts 30M household opportunity for its 5G fixed service[16], Mobile Experts believes that Verizon will be selective in markets, and neighborhoods within those markets, that they target based on fiber availability and market profile. While the growth rate is impressive, the actual unit shipment is expected to be modest.

It should be noted, however, that, if other major operators in Europe and APAC decide to push fixed wireless broadband service as a key pillar of their initial 5G applications, then our forecast will have to be increased according to the scale of ramp of those deployment. Currently, there is a lot uncertainty around this; hence, we have kept our forecast somewhat modest regarding unit shipments of 5G fixed.

[16] Verizon investor presentation on "5G Home Broadband," Nov. 2017

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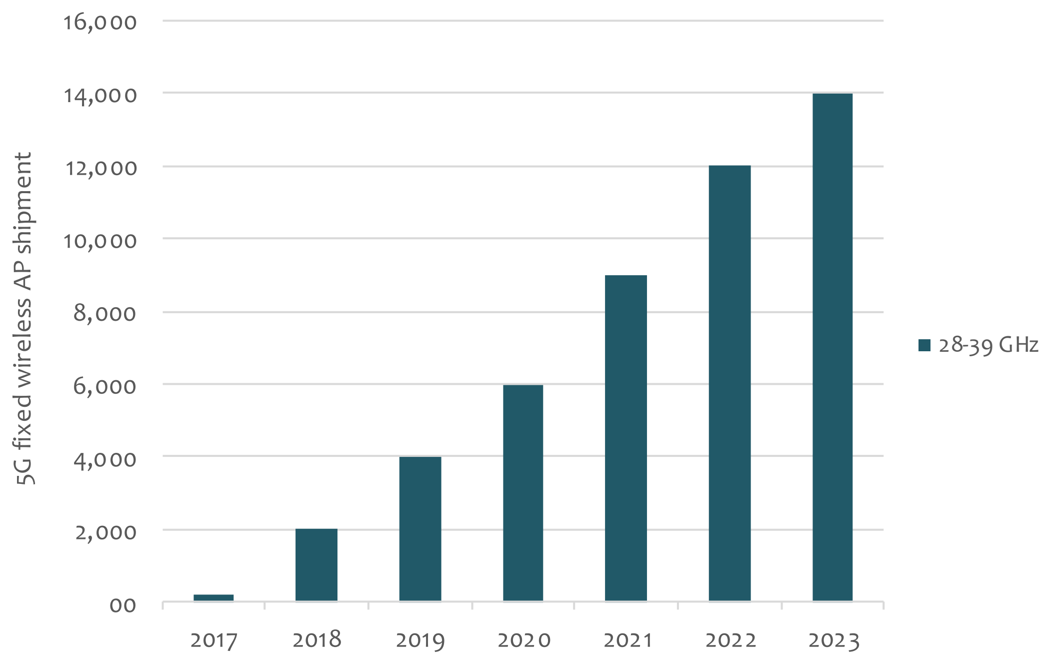

Source: Mobile Experts

Chart 6: 5G fixed wireless access AP shipment by freq. band, 2017-2023

FWA Equipment Forecast by Operator Type

The 802.11-based proprietary fixed wireless AP shipment volume will continue to be driven by the WISP operators. The WISP market is highly fragmented with many operators with limited scale in terms of AP's and subscriber counts. Many of these enterprising WISPs will be drawn to 802.11-based solutions with relatively lower infrastructure cost as compared to 3GPP-based solutions. However, as the market consolidates and larger players' preference for lower economics of LTE CPEs, the unit shipment to WISPs will gradually wane. At the same time, smaller regional telcos and some OTT competitive carriers with smaller scale fixed wireless launch will adopt 802.11-based proprietary solutions especially in higher-band millimeter wave solutions.

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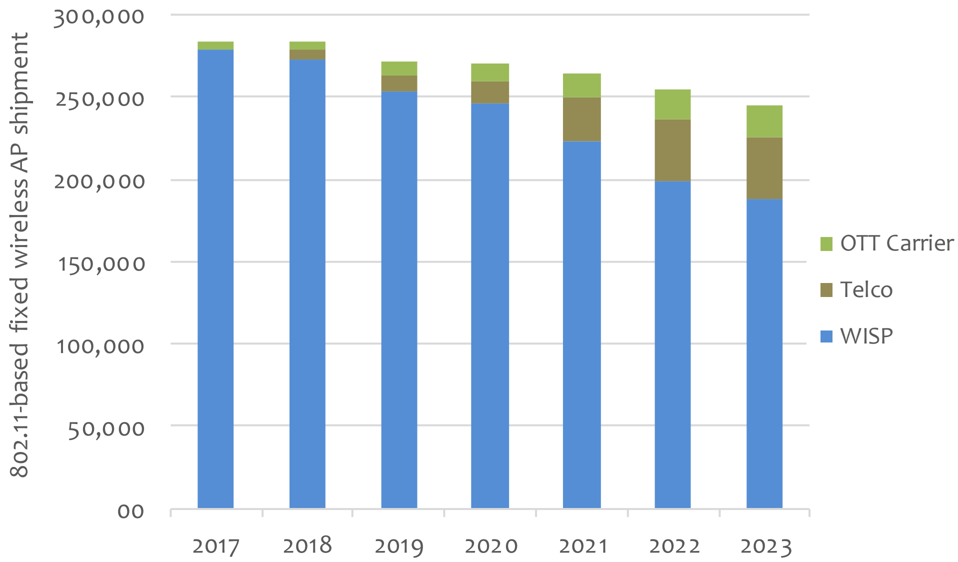

Source: Mobile Experts

Chart 7: 802.11-based fixed wireless access AP shipment by operator type, 2017-2023

The 3GPP-based (LTE and 5G) fixed wireless AP shipment volume will be driven by both WISP and mobile/telco operators. The WISP adoption of LTE solutions is driven by spectrum availability in the 3.5 GHz CBRS band as well as availability of LTE gear that operates in the 5 GHz unlicensed band. Moreover, advancements in the LTE small cell ecosystem has brought price-competitive LTE base station gear to the market to compete against “high-end” 802.11-based proprietary systems. While the price difference between “high-end” 802.11-based system like Cambium PMP 450 and LTE base station gear remains large, the cost differential has come down considerably when compared to a traditional LTE macro base station. Meanwhile, some mobile operators are opportunistically launching 5G fixed wireless systems in the millimeter wave bands, and tier 2/3 telcos are expected to leverage LTE fixed wireless to extend their broadband footprints through private funding or using government funding like CAF II.

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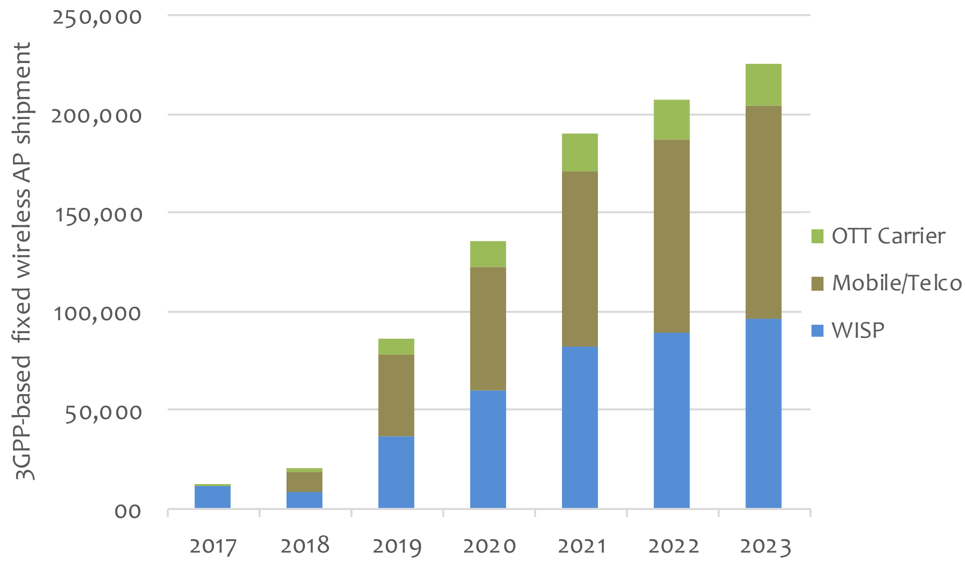

Source: Mobile Experts

Chart 8: 3GPP-based fixed wireless access AP shipment by operator type, 2017-2023

FWA Equipment Forecast by Market Density

Mobile Experts forecasts that the fixed wireless access market will predominantly serve the core rural market. While the new "micro hub" architecture opens up an opportunity to densify the network to address more dense suburban and urban market opportunities, we believe most of those opportunities will be addressed through either PtP or PtMP millimeter wave systems and that the bulk of 802.11-based AP shipments will be geared towards the rural market.

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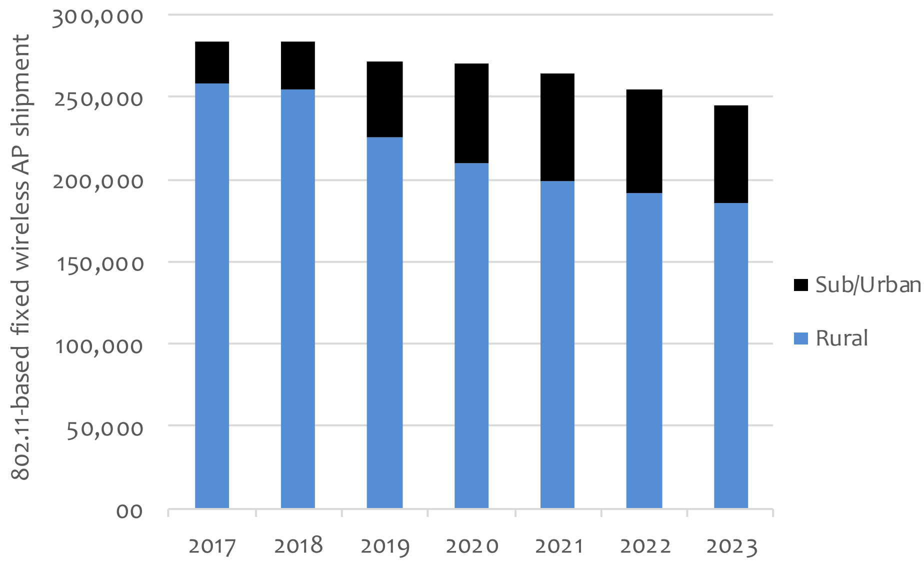

Source: Mobile Experts

Chart 9: 802.11-based FWA AP shipment by market density, 2017-2023

Mobile Experts expects the similar dynamic in the LTE and 5G fixed wireless space as well. Even though there is a greater opportunity to address suburban and urban fixed broadband opportunities with millimeter wave band, for example, we expect major mobile/telco operators to limit the scope of 5G fixed wireless deployment especially in the developed markets in North America and Europe. Fixed broadband penetration is already high in those regions, and the customer acquisition cost to take subscriber account away from formidable cable or fiber players may not be worthwhile. Instead, most of LTE fixed gears will be focused towards extending coverage in rural markets while opportunistically capturing market share in suburban and urban markets.

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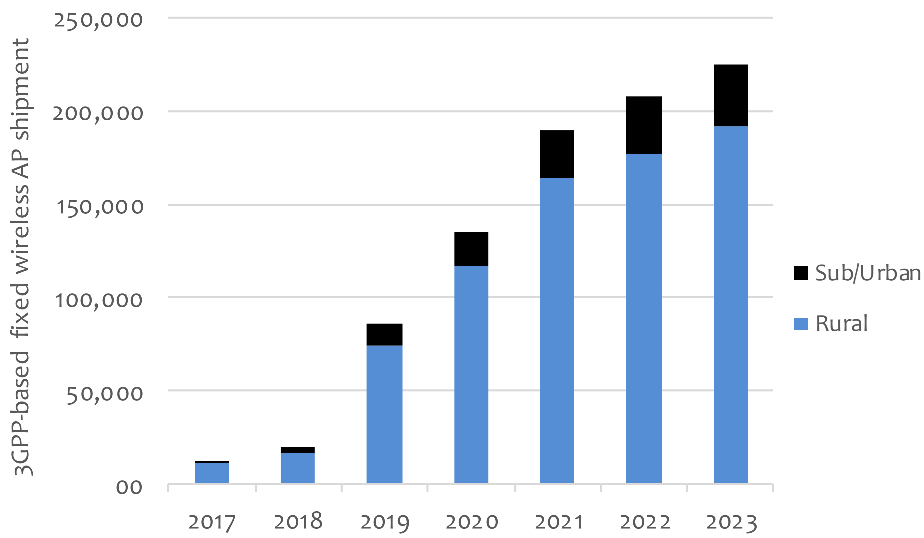

Source: Mobile Experts

Chart 10: 3GPP-based FWA AP shipment by market density, 2017-2023

FWA Equipment Forecast by Spectrum Bands

Operating frequency bands for fixed wireless access application span across the sub-1 GHz to 60 GHz millimeter wave bands. The unlicensed 5 GHz band is most popular band for fixed wireless due to its global scale, a good amount of spectrum bandwidth, and availability of both 802.11-based and LTE equipment gears. The use of 3-4 GHz and is expected to ramp up as the band gets opened up under CBRS rule (in the USA) and as "5G" designated band in other regions. Meanwhile, Mobile Experts forecasts steady unit shipments of millimeter wave fixed wireless AP equipment of both 802.11-based and 3GPP variety.

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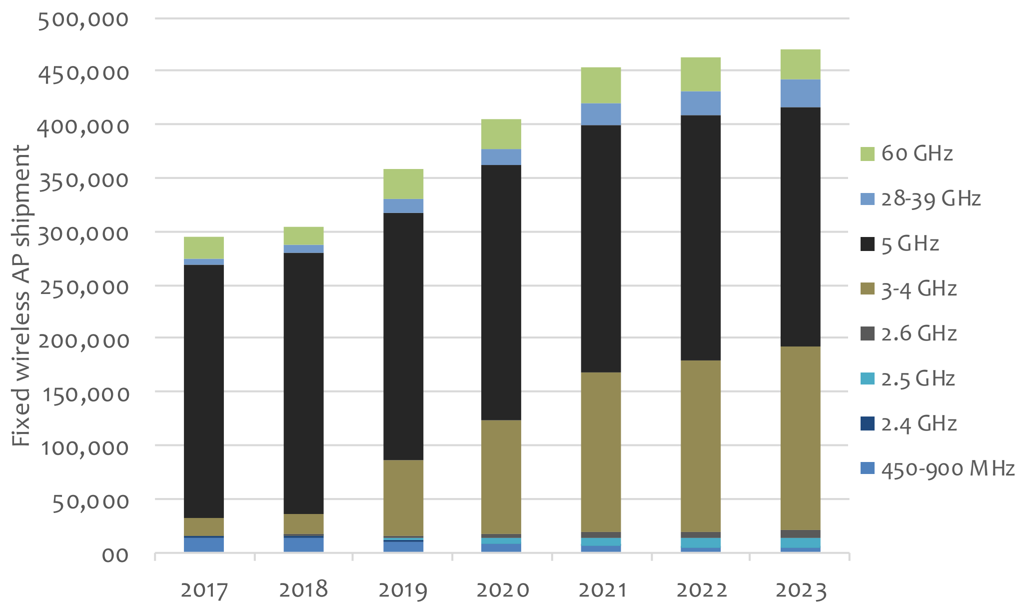

Source: Mobile Experts

Chart 11: Fixed wireless access AP shipment by spectrum bands, 2017-2023

Regional Analysis and Forecast

North America represents the largest market for "dedicated" fixed wireless base station AP equipment. With an estimated 3000 WISPs serving underserved broadband markets primarily in rural areas, North America has business environment that fosters this type of enterprising business. Fixed wireless broadband access business is a regional business; i.e., one does not need to have a nationwide scale to start (which is the case in the mobile wireless business). Anyone with entrepreneurial drive and some start-up capital can offer up broadband service after setting up a few base stations on air. The business can bootstrap from there. Europe and South America are other two significant market for fixed wireless as those regions have limited wireline broadband infrastructure. Hence, fixed wireless is cost-effective way to address the increasing broadband demand. APAC, in contrast, is not a huge market for "dedicated" fixed wireless AP market. The market is heavily dominated by large telecom players, and many are leveraging their mobile network to add fixed wireless broadband service.

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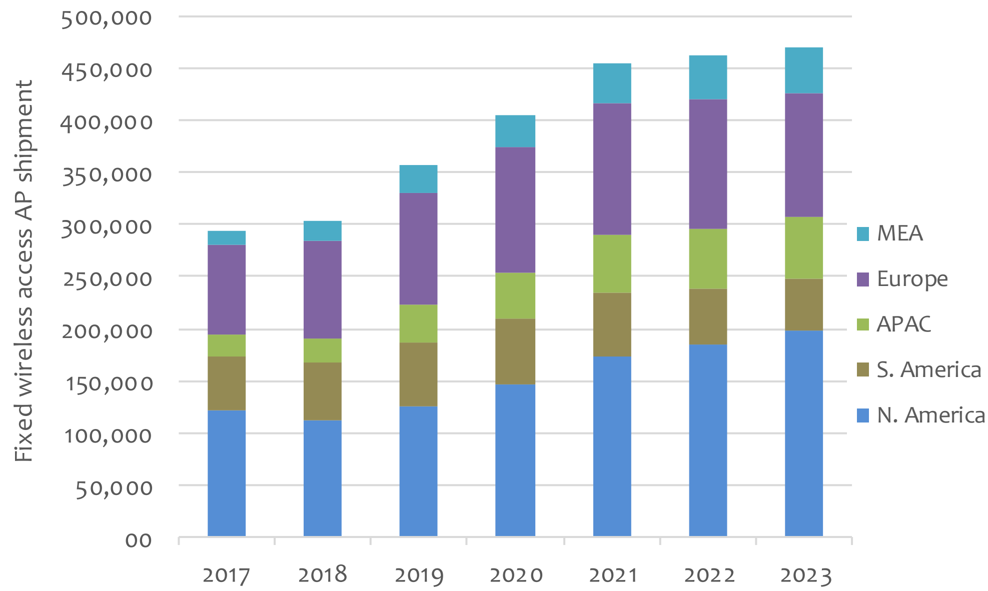

Source: Mobile Experts

Chart 12: Overall fixed wireless access AP shipment by region, 2017-2023

Regarding CPE shipments, APAC and Europe represent larger markets as the integrated mobile/telco operators are leveraging LTE mobile networks to address the growing broadband need. With about 40 MHz of spectrum, operators can deliver "tens of Mbps" broadband service. While some are using the same carrier channel for mobile and fixed service, some are looking to deploy dedicated channel carrier to ensure better quality. Due to the huge scale at which these large mobile operators can distribute CPEs, these regions are the key markets for (mostly LTE) CPE shipments. North America, in contrast, is relatively a small market for fixed wireless CPE's.

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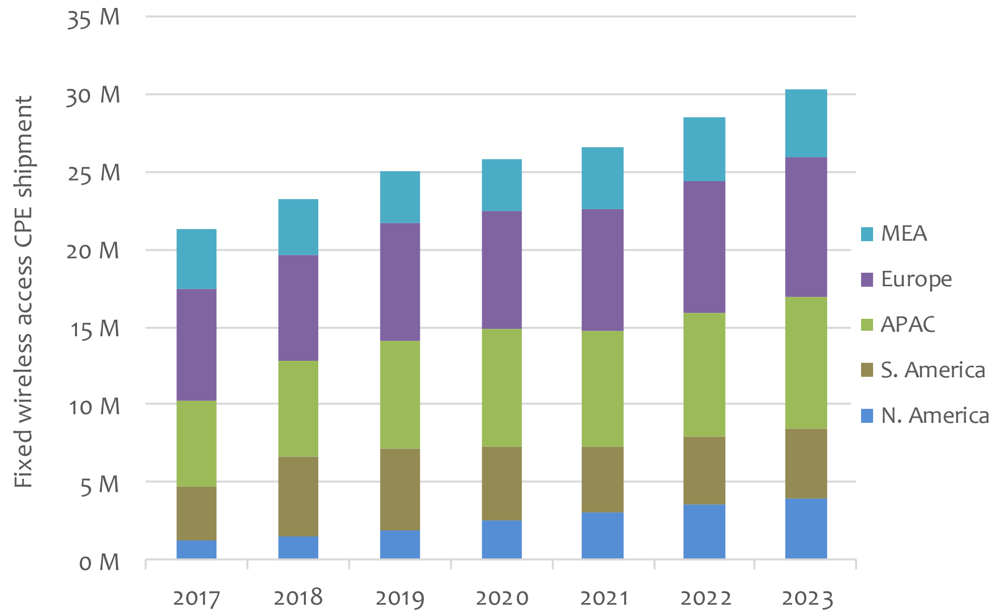
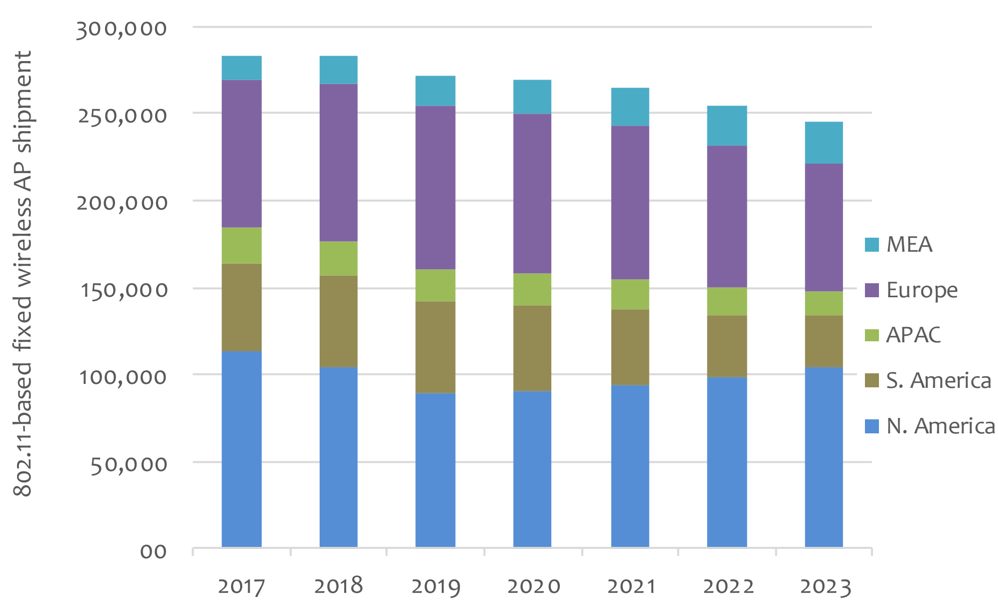


Source: Mobile Experts

Chart 13: Overall fixed wireless access CPE shipment by region, 2017-2023

802.11-based FWA Equipment Regional Outlook

While gradually declining, North America and Europe with robust WISP activities is forecasted to dominate 802.11-based priority fixed wireless AP equipment shipment.



Source: Mobile Experts

Chart 14: 802.11-based fixed wireless access AP shipment by region, 2017-2023

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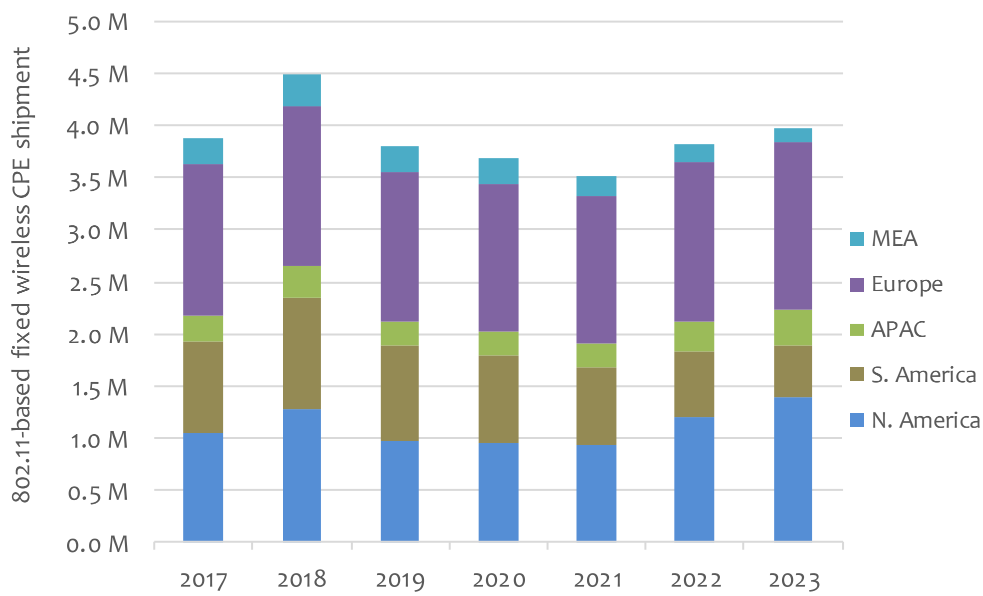
As the “micro hub” architecture is deployed to target more dense environments, especially in the developed regions like the USA, the declining “tower” 802.11-based access point count is expected to jump up. Meanwhile, some of the less-demanding broadband markets where expected broadband speeds are in the “tens of Mbps,” like parts of South America and Africa, Mobile Experts forecasts operators to increasingly leverage LTE-based mobile networks to provide fixed broadband services to maximize network utilization. Hence, traditional 802.11-based proprietary solutions that have serviced this market is expected to decline over time. It should be noted that a portion of these capital-constrained markets will continue to leverage low-cost 802.11-based solutions to build out rural markets.



Source: Mobile Experts

Chart 15: 802.11-based fixed wireless access CPE shipment by region, 2017-2023

3GPP-based FWA Equipment Outlook

The overall uptrend of 3GPP-based fixed wireless access base stations is expected to be largely driven by the CBRS adoption in the USA and mobile operators’ use of LTE mobile infrastructure to deliver fixed broadband service elsewhere especially in APAC, South America, and Europe. Moreover, 5G fixed deployment in select markets is expected to aid in the 3GPP-based AP shipment, but this portion is expected to be very modest.

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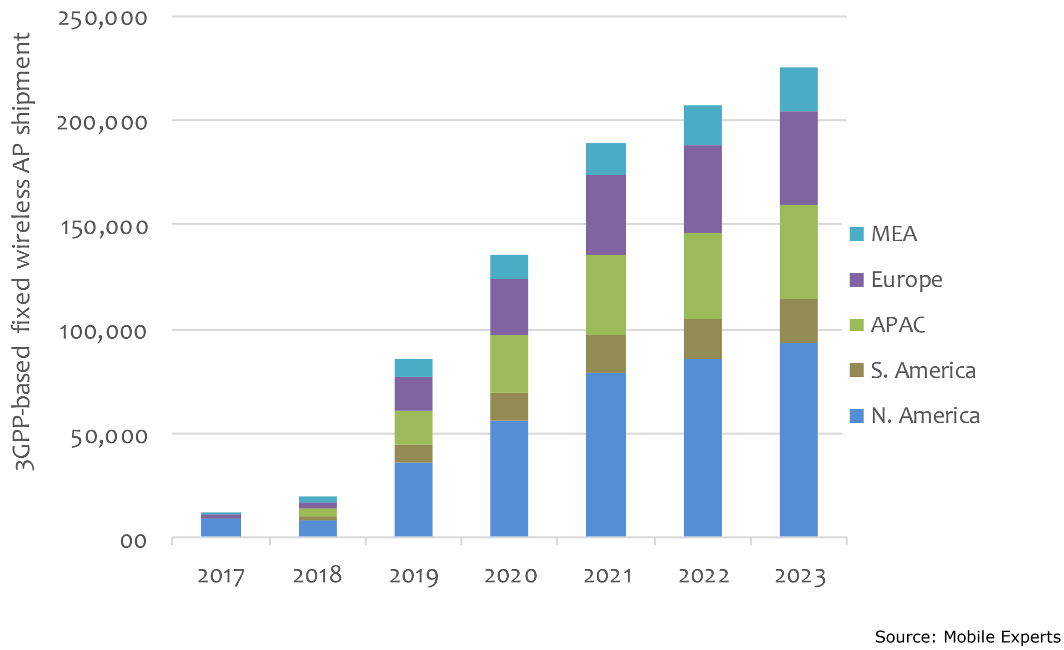

Chart 16: 3GPP-based fixed wireless access AP shipment by region, 2017-2023

The LTE CPE shipment is already in tens of millions annually. The trend of mobile operators shifting some of their mobile network infrastructure and spectrum towards fixed broadband is driving the unit shipments of LTE fixed CPE's. While this activity is pretty small among major mobile operators in North America, some of their 5G fixed trials and limited commercial launches are driving unit growth. However, the bulk of LTE fixed CPE shipment growth in the USA is expected to come from larger WISPs and more importantly telcos adopting fixed wireless to extend their wireline footprint.

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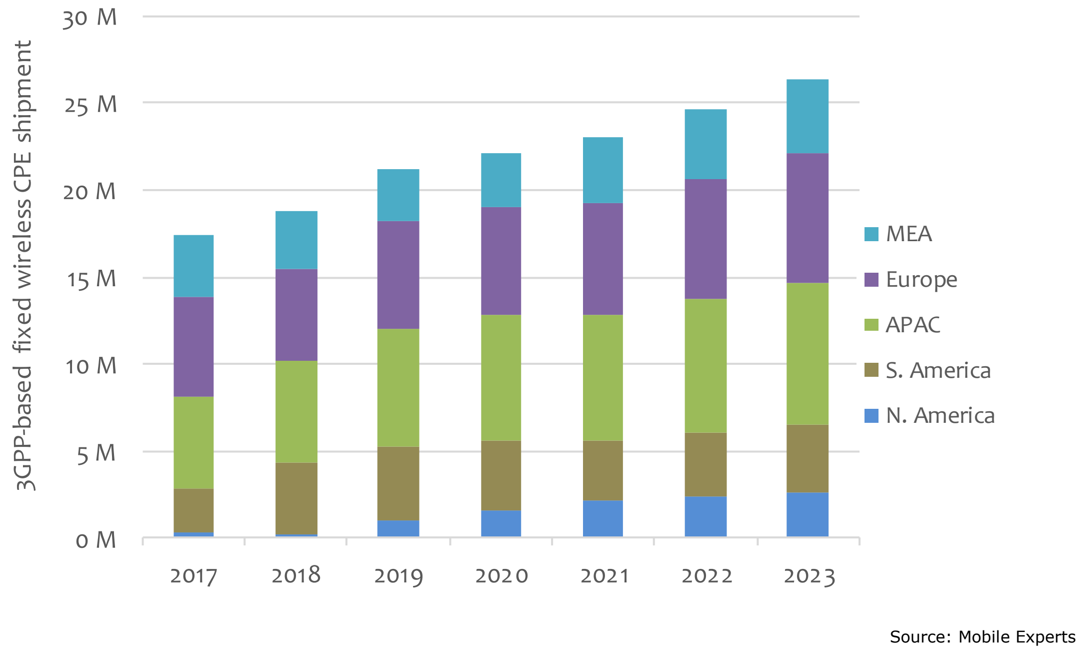

Chart 17: 3GPP-based fixed wireless access CPE shipment by region, 2017-2023

Fixed Wireless AP and CPE Equipment Revenue Forecast

The fixed wireless access equipment market is predominantly driven by customer premise equipment (CPE) shipments. For every base station access point installed, multiple CPE's are deployed to maximize the utilization of the shared base station AP and network capacity. The CPE segment of the fixed wireless access equipment market is expected to be flattish during our forecast period as the ASP price decline mutes a mid-single digit unit growth. Meanwhile the base station AP segment is expected to grow at 19% CAGR, rising to $1.2B in 2023. (*It should be carefully noted that our AP shipment count and revenue forecast does not include LTE base station AP shipments that are "shared" across both mobile and fixed. We primarily count LTE base stations dedicated for fixed wireless use, primarily by non-tier-1 mobile operators.*)

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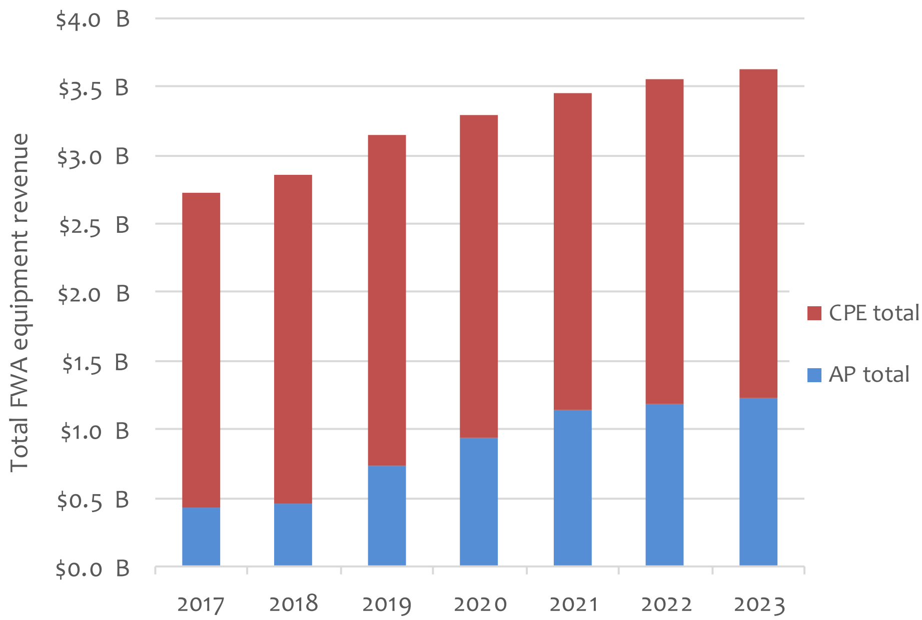

Source: Mobile Experts

Chart 18: Fixed wireless access equipment revenue forecast, 2017-2023

The base station AP market makes up a smaller portion of the overall fixed wireless access market. Excluding the mobile RAN base stations that are "shared" across both mobile and fixed services, the "dedicated" fixed wireless base station AP market is expected to rise quickly from about $429M in 2017 to about $1.2B in 2023. This demand for this "dedicated" LTE base station AP's will come from tier 2/3 telcos without mobile operations and larger WISPs. It should be noted that the 5G fixed AP revenue is largely driven from selective tier-1 5G fixed wireless launches, including Verizon's 5G Home Broadband service. The 5G fixed equipment contribution is expected to be minimal. (*Our conservative view of 5G fixed adoption is based on our view that competitive dynamic between mobile and fixed or cable players will be largely muted. If the competitive intensity between these two segments of the market increases, we believe the 5G fixed adoption will be accelerated and thus increase our overall forecast of 5G AP and CPE shipments.*)

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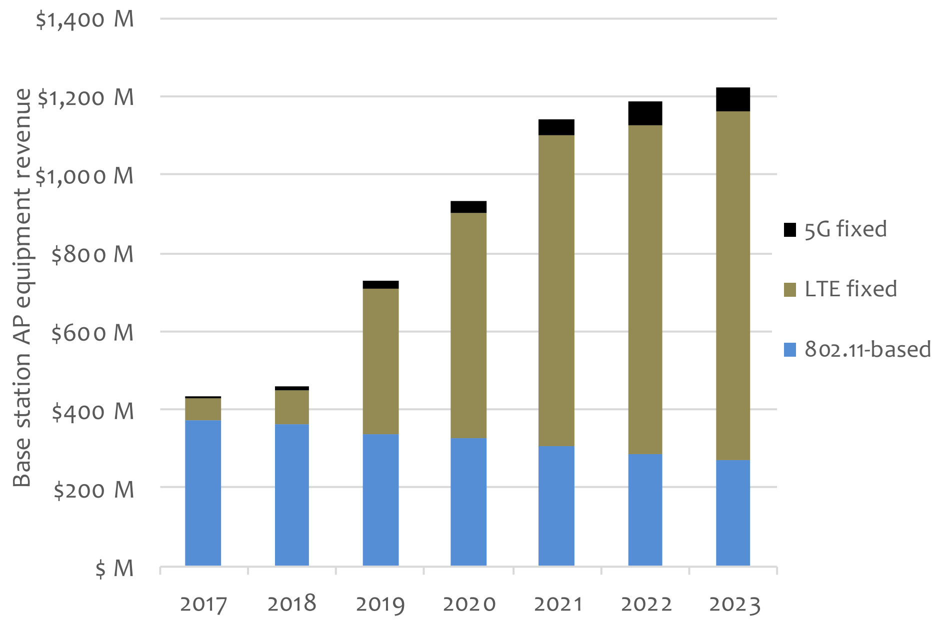

Source: Mobile Experts

Chart 19: Fixed wireless access base station AP revenue forecast, 2017-2023

As noted earlier, the fixed wireless access equipment market is dominated by CPE shipments. Within this segment, LTE CPEs used for fixed wireless broadband service already constitutes over three-quarters of the overall fixed CPE share and is expected to increase its share to about 80% by 2023. The overall fixed wireless CPE market is forecasted to remain flat during the forecast period as modestly growing LTE CPE market is offset by declining 802.11-based proprietary CPE market. The 5G fixed CPE market is forecasted to grow quickly from a very small base, and represent about 3% of the total fixed CPE market by 2023.

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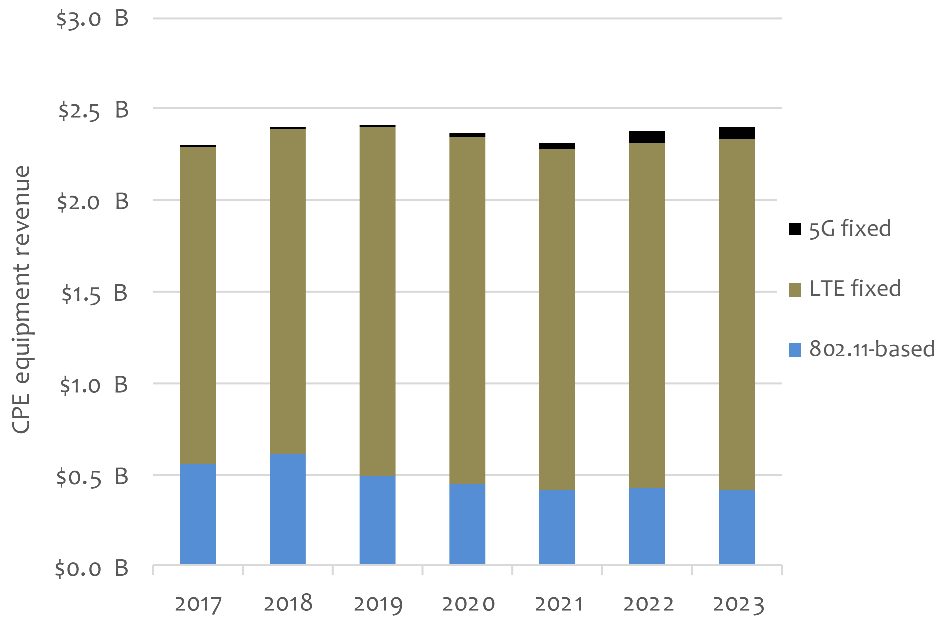

Source: Mobile Experts

Chart 20: Fixed wireless access CPE revenue forecast, 2017-2023

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7. COMPANY PROFILES

AT&T

AT&T is a major integrated mobile/telco operator with multitude of network assets from nationwide wireless, fiber, copper, and satellite assets. The company is using its WCS spectrum dedicated for its fixed wireless broadband service mostly in rural areas to fulfill its CAF commitment. The company plans to cover 1 million residential and business locations by 2020.

BaiCell

Founded in 2014, Baicells is a privately-held company based in Beijing, China. The company's product solutions range from indoor and outdoor small cells, CPEs, and antennas. With a new sales office in the USA, the company is targeting the WISP market with its outdoor LTE small cells including those that operate in the 3.5 GHz CBRS band.

Cambium Networks

Cambium was formed in late 2011 after the original Motorola Canopy business was sold to a private equity. The company has a few R&D centers around the globe with its headquarter based in Rolling Meadows, IL. The company is believed to have about 500 employees with about $200M in revenue. Its PMP 450 platform has been widely deployed around the world, and the company provides both PtP and PtMP radio gears across a wide swath of spectrum bands. The company's product is considered "carrier" class among the WISP operators, and its product pricing reflects this as compared to some of its lower-cost peers.

Cambridge Broadband Networks (CBNL)

CBNL is a UK-based company, which has been around since 2000, developing point-to-multipoint radios mostly in high-frequency bands. Its gears are widely deployed for access and backhaul for high-capacity enterprise access market. With high CPE cost associated with millimeter wave bands, it has found its niche in the enterprise fixed wireless space. The company had a limited fixed wireless deployment with Windstream in the 28 GHz band. It is an innovator in the PtMP millimeter wave radio. The company works with major service providers for niche fixed wireless deployments targeting enterprises in developing regions where wireline broadband is limited.

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CenturyLink

As one of the major telcos in the USA, CenturyLink has a wide range of telecom assets through recent acquisitions of Level 3 and enterprise business. As one of the "price cap" carriers for the CAF funding to deploy broadband access in underserved areas, CenturyLink is exploring fixed wireless access systems to deploy in the primarily rural markets in the CAF designated areas.

Consolidated Communications Holdings (CNSL)

CNSL is a leading broadband and business communications provider serving consumers, businesses of all sizes and wireless companies and carriers, across a 24-state service area, covering mostly Midwest, Northeast, Southeast, Texas, California, and Washington. The company serves over 1.5 million connections. Leveraging its advanced fiber optic network spanning more than 36,000 fiber route miles, Consolidated Communications offers a wide range of communications solutions, including data, voice, video, managed services, cloud computing and wireless backhaul.

C Spire

Also known as Cellular South, C Spire is a regional telecom operator based in Ridgeland, Mississippi, and is the sixth largest wireless provider in the USA with an estimated 1 million mobile subscribers. The company has launched its "25 Mbps" fixed wireless service in eight markets, initially targeting 70,000 residential and business customers. The company announced that it would cover 200,000 customers with fixed wireless service and another 50,000 with FTTH.

Frontier Communication

Frontier Communication is a tier 2 telco with numerous wireline connections, many of which it has acquired from Verizon. For example, it has acquired Verizon's FiOS footprint in Texas, Florida, and California in recent years. The company has confirmed that it is testing fixed wireless to address broadband connectivity to underserved areas. Frontier, like other tier 2 operators, who have received CAF funds to address broadband availability are actively evaluating fixed wireless solutions.

Huawei

Huawei is a major global RAN vendor. With its incumbent position in the huge China mobile infrastructure market, the company has been actively growing its fixed wireless business primarily through leveraging the installed base of its LTE base stations and providing LTE CPEs to its mobile operator customers to expand into fixed wireless broadband access market. Under the "WTTx" (wireless to the X)

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product/business line name, the company is seeing a good growth in APAC and other markets.

Intracom Telecom

Based in Greece, Intracom Telecom has a long history in the market in delivering product solutions for wireless backhaul and broadband wireless access systems. It has 28 GHz PtMP product branded as "WiBAS-Connect" that is targeted for the fixed wireless access market. Also, it offers 60 GHz V-band and E-band PtP products for backhaul.

Linkem

Linkem is Italy's largest WISP that has over 1200 base station antennas, serving over 2000 municipalities in Italy. Its wireless network covers 40% of Italy's land mass. It has been transitioning its original WiMax network to LTE. It has LTE coverage in the 3.5 GHz band.

MikroTik

MikroTik is a Latvian company founded in 1996. It has a long history in the fixed wireless industry offering very low-cost radio and networking gear for WISPs. Its company profile is similar to Ubiquiti except that MikroTik still largely work with Wi-Fi chipset companies and create hardware and surrounding software solutions for WISPs. Ubiquiti, on the other hand, has ventured into creating its proprietary chipset solution for its radio products. MikroTik has a strategic relationship with Qualcomm in leveraging Qualcomm's Wi-Fi chipset solution as an underlying baseline for its access, backhaul, and CPE products.

Mimosa Networks

Founded in 2012, this Silicon Valley-based company sells mostly unlicensed PtP and PtMP radios for backhaul and access. The company has been promoting "Micro Pop" architecture to essentially densify fixed wireless networks into denser markets. The company is one of the leading voices in the Broadband Access Coalition to open up the 3.7 – 4.2 GHz band for fixed wireless.

Nokia

As one of the leading global RAN vendors, Nokia has a wide spectrum of RAN products. For the fixed wireless access market, the company is initially targeting 60 GHz unlicensed gear to "1 Gbps" wireless broadband access. Organizationally, the company fixed wireless product group is a part of its Fixed Networks business (along with PON, Cable products).   The company's 60GHz PtMP gear appears to be

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primarily focused on traditional mobile/telco operators looking to provide wireless alternative in denser environments.

Radwin

Headquartered in Tel Aviv, Israel, Radwin provide a suite of PtP and PtMP radio products for WISP and Carriers. Under the product branding of "JET" series, the company offers 5 GHz and 3.5 GHz radio gears for the WISP market. In addition to the fixed wireless access market, the company is positioning its JET products for Smart City and IoT applications to broaden the market appeal.

Redzone Wireless

Redzone Wireless is one of leading WISPs in the USA serving over 100 communities in Maine. The company uses LTE on 2.5 GHz band and "5 GHz" technology to cover 225,000 households and 40,000 businesses across the state.

Rise Broadband

Rise Broadband, headquartered in Englewood, Colorado, is the largest WISP in the USA with about 200,000 residential and business customers. It has acquired over 100 WISPs since launching the company as JAB Wireless in 2005. The company has a combination of LTE and 802.11-based proprietary base stations in service. The company's annual revenue exceeds $200M and has over 800 employees.

Samsung

Samsung Networks is one of the key radio vendor for Verizon's 5G fixed trials and commercial launch. It has a history of delivering macro and small cell solutions to Jio in India and is obviously one of the top two smartphone suppliers in the world. Samsung has its millimeter wave modem and RFIC which are instrumental in its 5G small cell products as well as enterprise-class LTE small cells and Wi-Fi access points.

Siklu

Siklu has a long history of delivering wireless backhaul solutions to WISPs and carriers. Based in Israel, the company was founded in 2008 and has recently gone through a management change. It has 70/80 GHz point to point backhaul product as well as 60 GHz PtMP product that is it shipping today. Its leading market is North America with some market activities in Australia, UK, Germany, and Africa.

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Starry

Based in Boston, Starry has developed proprietary 37 GHz PtMP fixed wireless system leveraging underlying WI-Fi chipset solution from Marvell. Its "200 Mbps for $50" broadband service is now active in Boston and has announced further rollout of its network to 16 additional markets over the next year. Unlike traditional WISPs, Starry is targeting denser sub/urban markets leveraging large chunks of spectrum in the millimeter wave bands and highly capable (and costly at today's small-scale) CPEs to extend the millimeter wave coverage.

Telrad

Telrad offers LTE gear for WISPs in the 2.5 and 3.5 GHz band. It has recently signed an agreement with Federated Wireless to extend operation of its LTE gears in the CBRS bands. The company touts software-defined radio capabilities from its Alvarion acquisition. The wider Telrad parent company based in Israel has other businesses related to telecom.

Ubiquiti (UBNT)

Ubiquiti has a long history of delivering very low-cost radio gears for the WISP market. Under the AirMax brand, the company offers PtMP fixed access products across many spectrum bands. The AirFiber brand is associated with its wireless backhaul products with long range and capacity. The company has been touting its next-generation "LTU" platform which supports OFDMA (like LTE and 802.11ax) and other features to boost sector capacity and subscriber throughput speed. In the meantime, the company has created successful enterprise Wi-Fi access point product line which is growing faster than its original root in the fixed wireless industry.

Windstream

Like its tier 2 telco peers, Windstream is believed to be exploring fixed wireless solution to meet its CAF commitment. Windstream already offers fixed wireless to its enterprise customers. It has launched 28GHz PtMP network in a handful of cities, but the network's future is uncertain as a result of Verizon acquisition of Straightpath whose spectrum was used in that network.

Verizon

As one of the leading operators in the world, Verizon has been at the forefront of 5G technology development. In addition to small cell deployments that are on-going, Verizon has actively trialed millimeter wave fixed wireless service in 11 markets, including Ann Arbor, Atlanta, Bernardsville, NJ, Brockton, MA, Dallas, Houston, Denver, Miami, Seattle, Washington, DC, and has announced commercial fixed

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wireless service launch in 3 to 5 cities, including Sacramento, in the second half of 2018 with a broader rollout planned in 2019. Verizon has acquired significant 28 and 39 GHz spectrum through XO and Straightpath acquisitions.

Vivint

Based in Utah, Vivint is a major "smart home" service provider including home monitoring, video security, etc. The company's annual sales reach $700-800M. The company built out fixed wireless network in Salt Lake City, a couple of cities in Texas. It is currently exploring new technology and spectrum options to extend its fixed wireless business.

ZTE

As one of the major supplier of wireless infrastructure, ZTE provides RAN gear to domestic telecom operators in China as well as select customer base throughout the world. The company offers LTE gear for use in unlicensed bands for WISP market.

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8. GLOSSARY

2G:	Second Generation Cellular
3G:	Third Generation Cellular
4G:	Fourth Generation Cellular
5G:	Fifth Generation Cellular
802.11:	IEEE standard for local area networking (extended to fixed wireless)
ADSL:	Asymmetric Digital Subscriber Line (slower DSL technology)
AP:	Access Point (Base Station)
BBU:	Baseband Unit
BRS:	Broadband Radio Service (FCC designation in the 2.5 GHz band)
CAF:	Connect America Fund
CBRS:	Citizens Broadband Radio Service, a shared wireless broadband use of the 3550-3700 MHz (3.5GHz) band in the US
CLEC:	Competitive Local Exchange Carrier
CPE:	Customer Premise Equipment (e.g., cable modem, broadband gateway)
CRAN:	Centralized RAN
DFS:	Dynamic Frequency Selection
DSL:	Digital Subscriber Line (copper-based broadband technology)
EBS:	Educational Broadband Service (FCC designation of the 2.5 GHz band)
FCC:	Federal Communications Commission (US telecom regulator)
FPGA:	Field Programmable Gate Array
FTTH:	Fiber-to-the-Home
FWA:	Fixed Wireless Access
GAA:	General Authorized Access (in context of CBRS)
GHz:	Gigahertz
HD:	High Definition
IP:	Internet Protocol (or Intellectual Property)

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ITU:	International Telecommunications Union
LAA:	License Assisted Access
LTE:	Long Term Evolution
MAC:	Media Access Control (layer 2 in OSI model)
MDU:	Multi Dwelling Unit
MHz:	Megahertz
MIMO:	Multiple input, multiple output spatial multiplexing
MU-MIMO:	Multi-User MIMO
mmW:	millimeter wave
nLOS:	near Line of SIght
NLOS:	Non Line of Sight
NR:	New Radio (in context of 5G)
OTT:	Over the Top (Competitive Carrier)
PAL:	Priority Access License (in context of CBRS)
PtMP:	Point to Multi-Point (one to many radio link)
PtP:	Point to Point (one to one radio link)
RAN:	Radio Access Network
RF:	Radio Frequency
ROI:	Return on Investment
RRH:	Remote Radio Head
SAS:	Spectrum Access System
TDD:	Time Division Duplexing
TDMA:	Time Divison Multiple Access
U-NII:	Unlicensed National Information Infrastructure
USF:	Universal Service Fund
WCS:	Wireless Communications Service (2305-2320 and 2345-2360 spectrum)
Wi-Fi:	Wireless Fidelity (unlicensed wireless communications)
WiGig:	Wireless Gigabit (60 GHz unlicensed band)
WISP:	Wireless Internet Service Provider (independent FWA operator)

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9. METHODOLOGY

To create estimates and forecasts for Fixed Wireless Access equipment shipments, Mobile Experts relied on direct input from more than 20 industry sources, including input from multiple wireless ISPs contributing to the overall analysis to give a detailed global view of the market. Mobile Experts built a "top-down" forecast based on direct input from operators, as well as overall trends in end-user demand for mobile services. Then, Mobile Experts built a "bottom-up" forecast through discussions with the supply chain, including vendor suppliers, top-tier OEMs, and component suppliers. Mobile Experts also used financial disclosures from publicly traded companies to assemble a quantitative view of the equipment market.

Mobile Experts has defined market segments in a new way to achieve more clarity than other analysts in this area.

In particular, Mobile Experts has clearly drawn a distinction in this report between 3GPP fixed wireless access and 3GPP mobile access. Fixed users are defined as those with a CPE in a set location, at a home or office. If a base station is "shared" between mobile users and fixed users, then it's not counted here.

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